Design of Nanomanufacturing Systems

by

Alexander H. Slocum, Jr.

S.B. Mechanical Engineering
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ABSTRACT

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Over 100 years of manufacturing knowledge and experience are available to a design engineer when considering the integration of a machine tool enabling macro-scale processes (milling, turning, welding, water-jet cutting) into a production or manufacturing line, and this thesis seeks to provide a design engineer with the insight so that the same can be done for a nano-scale process such as Dip Pen Nanolithography and Nanoimprint Lithography. Accordingly this work presents methods for designing nanomanufacturing systems, including the development of new technology to fulfill the unique performance requirements of nanomanufacturing processes. First, an introduction to nanomanufacturing and the differences between macro-scale and nano-scale manufacturing will be presented. Second, a "metric mapping" method will be illustrated which can be used to identify areas of nano-manufacturing where the need for the development of new technology is critical. Thirdly, this new method is capable of helping a design engineer synthesize technology for nano-manufacturing, as will be shown through a case-study in which a modular, precision belt-drive machine which is capable of enabling high-throughput nanomanufacturing was designed and built. This machine for high-rate nanomanufacturing not only exceeds the performance requirements for a process (Dip Pen Nanolithography, or DPN) that has been called "not suitable for high-rate nanomanufacturing", but also is capable of implementing DPN at a rate almost 200 times that of previous machines.

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1

INTRODUCTION

The goal of this thesis is to show that high-throughput nanomanufacturing is possible. A high-precision, high-throughput, belt-driven nanomanufacturing machine has been designed, fabricated, and shown to a) enable a nanomanufacturing process and b) achieve the required performance to meet the unique needs of nanomanufacturing. In addition to this machine, a design methodology has been developed (Metric Mapping) to help a design engineer identify areas of nanomanufacturing technology in which the development of new manufacturing technology is critical. In order for the full potential of nanotechnology to be realized, nano-scale products must be mass-produced in a cost-effective and efficient manner. The current state of devices used to enable nanomanufacturing processes in a laboratory setting is evidence of the need to drastically increase throughput and move production from the laboratory to the factory. This is an essential step if the full impact of nano-technology is to be realized by society.

History has shown that in general, either the science behind a manufacturing process leads to the development of new technology to enable it [1], or a new technology is developed which then leads to scientific investigation into developing an understanding of the processes. Computer-Numerical-Controlled milling was first demonstrated in a laboratory at MIT, long before it was integrated into manufacturing lines. This practice (of technology developed to meet a need in manufacturing) does not show any sign of wavering; the development of new nanomanufacturing processes has generally begun with research, and once a nanomanufacturing process has been demonstrated to be feasible in the laboratory, the focus should then ideally shift to turning it into a manufacturing process.

Electro-discharge machining (EDM), abrasive waterjet technology, Computer-Numerically-Controlled Machines, and wafer-steppers used in the manufacture and testing of semi-conductors are but a few of the many examples in which a process was first developed and perfected, and the design of the machine architecture and supporting technologies came second. Nanomanufacturing is currently at a similar stage: the science behind a process exists and a general understanding of how the process works has been achieved; the technology does not exist, however, which is required to enable that process to mass-produce nano-scale products.

Attempting to deliver a single machine or idea that will satisfy the needs of nanomanufacturing as a whole is not a currently viable solution. The nanomanufacturing industry has not yet matured into the broad, unified entity that is, for example, the automobile manufacturing industry [2, 3]. Furthermore, the current state of nanomanufacturing technology is analogous to that of the ruling engines used to make diffraction gratings before the development of the Johns Hopkins Ruling Engine by John Strong in the 1950s [4], see in Figure 1.1.

Prior to Strong's Ruling Engine, the need for a more accurate and precise method of manufacturing diffraction gratings was needed as the limits of performance of Rowland-type ruling engines were being reached. Henry Rowland, a Professor of Physics at Johns Hopkins in the late 1800s, developed the ruling engine which bears his name. His device, and the diffraction gratings manufactured with it, helped to usher in the field of modern astrophysics.

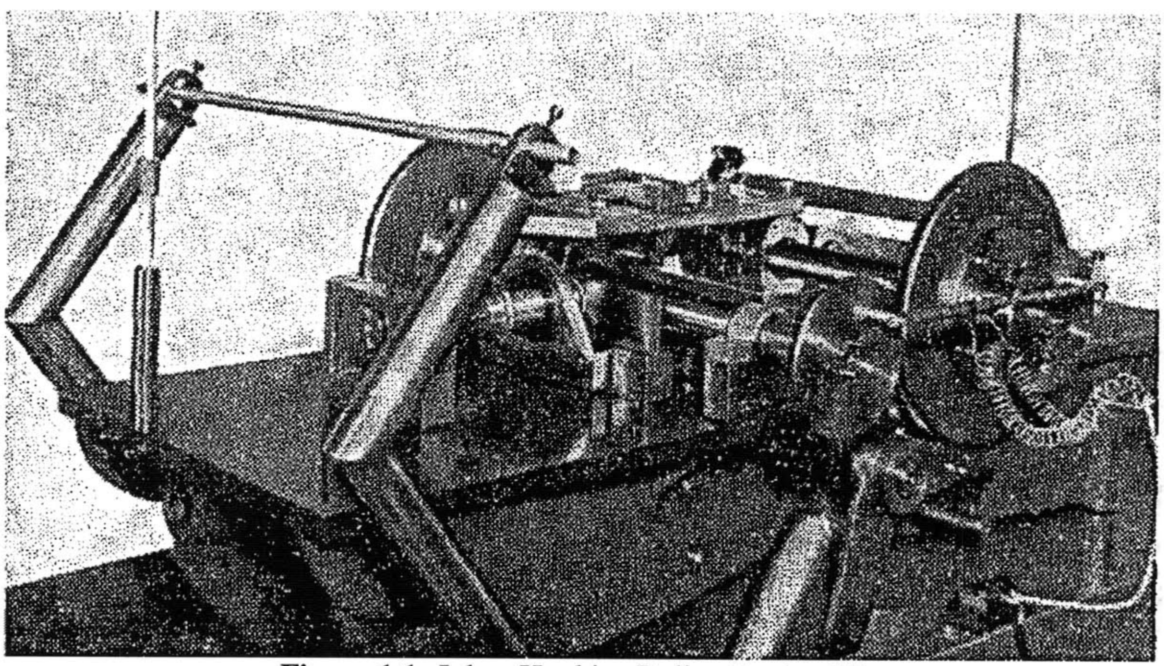

Figure 1.1: Johns Hopkins Ruling Engine [4].

It should be noted that this thesis does not seek to revolutionize the field of nanomanufacturing in the same way Strong's ruling engine revolutionized the production of diffraction gratings, and in turn astrophysics. It does however, seek to highlight the fact that there are a number of lessons that can be learned from history; taking them into account when designing nanomanufacturing machines can enhance a design engineer's ability to more rapidly enable processes still in the "laboratory" stage. Additionally, history shows that history has demonstrated that history repeats itself (etc.). It would behoove any good engineer, when attempting to design machines to enable nanomanufacturing processes to take advantage of the fact that nanomanufacturing is in it's infancy, with plenty of room to make significant contributions designing the latest and greatest nanomanufacturing machines.

Manufacturing technologies to enable any nanomanufacturing processes on a large scale are absolutely necessary to take full advantage of the impact a process can have on society [5]. "For nanotech products to achieve the broad impacts envisioned, they must be manufactured in market-appropriate quantities in a reliable, repeatable, economical and commercially viable manner" [2, 3]. Furthermore, in keeping with the "historical perspectives" approach to designing and building new nanomanufacturing equipment, a relatively brief account of the history of manufacturing is presented. A consideration of certain technological advancements and their impact on the world is also made; parallels are drawn between the invention of those technologies and what has been developed so far in order to enable nanomanufacturing on a large scale.

1.1 Manufacturing Systems

One of the earliest examples of manufacturing systems came about in the early 1800s, through the work of Captain John H. Hall and his system of interchangeable parts. Hall designed and manufactured 1000 M1819 rifles for the US Army in 1819, using interchangeable parts and precision machined components that were critical to the rifle's performance. Hall's Rifle Works, on Lower Hall Island in the Shenandoah River, was the site of critical contributions to the American system of manufacturing. These included the straight-cutting machine (the forerunner of the modern milling machine), and a workshop that, at the time, "mass-produced" firearms using machines operated by boys, not by skilled craftsmen. Captain Hall's work in the manufacture of firearms laid the foundation for the development of mass production in America.

Henry Ford's realization of the need for "a light, low-priced car..." led to the perfection of its governing principles in the early 20th century. Even more important than the development of mass-production at Ford was the diffusion of those ideas and techniques throughout the industrialized world of the early 1900's. The Ford Production System outlined a method and techniques for mass-producing a specific product (in this case the Model T). Its effectiveness is evident in the fact that the 15,000,000th Model T Ford rolled off of the production line just 15 years after being introduced to the public [6, 7].

What is important to note is that:

1. A historical perspective can be used to make improvements on existing technology and identify areas of developmental need;
2. The development of *new* technology to perform where existing technology doesn't follows suit;
3. Both 1 and 2 can be utilized to do something that previously couldn't be done (and was originally thought to be impossible).

Take for example the differences between the first M1819 rifles and the latest Model Year 2010 luxury sports car. It is humbling, yet enabling, to know that the luxury sports car owes its very existence to the M1819 rifle. In 1819, an automobile from 2010 would have been alien, achieving things that would have appeared the work of magicians (such as GPS). Knowing that today's most technologically-advanced luxury car could be the M1819 rifle to the nano-technological achievements of the very near future provides sufficient motivation to start developing technology and tools for enabling nanomanufacturing.

It is essential that the reader possess a basic understanding of manufacturing technology. If the reader is a newly-minted engineer, it is suggested that the following be reviewed to ensure a solid understanding of the principles of manufacturing discussed herein. If the reader is a well-oiled practicing engineer, it might still be a good idea to at least skim the following sections for a brief review of manufacturing systems and terminology, and to make sure that those terminologies used in this thesis are in alignment with their own.

1.1.1 Why Manufacturing?

Now, on to the good stuff: what is manufacturing? Why do we need manufacturing? Webster's New-World Dictionary defines the word "manufacture" as: *"the making of goods,* *especially by machinery on a large scale". On a large scale* is critical here, because without manufacturing technology, there would be no public transportation, there would be no computers and the world as we know it today would be drastically different. Manufacturing is one of the key elements that enabled the industrial revolution, and altered the course of human history.

An organized, efficient, and cost-effective manufacturing process allows for large quantities of product to be made and delivered to the customer with smaller lead times, and at lower cost, than if a more stochastic process was used with no organization present. Plain and simple: if you want to make a lot of something (and sell it at a price that a large number of people can afford) some sort of manufacturing system must be implemented to make it. In order to manufacture nano-products in a cost-effective manner, nanomanufacturing equipment is necessary to meet this need.

A piece of nanomanufacturing equipment is a precision machine. It has been said (regarding precision engineering), that "...precision engineering is dedicated to the continual pursuit of the next decimal place." From the website of the American Society for Precision Engineering (www.aspe.net), "the field of precision engineering encompasses elements of machine design including but not limited to: controls, dimensional metrology, history of precision engineering, instrument/machine design, nanotechnology, scanning microscopes, and ultra-precision machining". If part of what makes a precision engineer is a keen awareness of the history of the field when designing new machines, it would also make sense for extensions of precision engineering, such as the manufacture of nanotechnology using precision nanomanufacturing machines, to be aware of the history of manufacturing systems as well.

1.2 Manufacturing System

A discussion of manufacturing consists of three main elements: manufacturing systems, manufacturing equipment and/or machine tools, and the manufacturing processes which are enabled by the first two. There are three general classifications of manufacturing systems, with the latter two elements (machines and processes) being far too broad and diverse to address thoroughly in this thesis. These manufacturing systems have evolved over the decades of development of manufacturing technology, and are as follows: the Job Shop (JS), the Flow Shop (FS), and the Machining Cell (MC). These manufacturing architectures are discussed in the following sections. An example of each process is given, as well as a representative product that is manufactured utilizing that process.

It should be noted that the three classifications of manufacturing systems (job shops, flow shops and machining cells) can be further broken down into 7 different *types* of manufacturing systems [8], as seen in Table 1.1:

Table 1.1: Different types of manufacturing systems.

Mfg System Type	Mfg System Sub-Type
1. Job Shop	
Machining Cell	2. Batch flow
	3. Operator-paced line flow
	4. Equipment-paced line flow
	5. Flexible manufacturing system
	6. Just-in-time (JIT) manufacturing systems (a cornerstone of the Toyota Production System)
7. Continuous-Flow shop	

Systems 1 and 7 are easily differentiable from each other and also the other manufacturing systems. Systems 2-6 however, are similar in terms of their characterization with respect to the manufacturing variables of rate, cost, quality, and flexibility. As such, these are lumped into the machining cell classification. Job shops, flow shops, and machining cells are fundamentally different in their operational characteristics and their ability to meet the needs of certain manufacturing applications.

1.2.1 Flow Shop

A flow shop is generally composed of lines of machinery (manufacturing or assembly lines), dedicated to making or assembling a specific part or parts. The shop can have a main line for assembly, with smaller feeder lines which manufacture the parts, or any other configuration which can be thought of by the reader. A flow shop is relatively rigid in its layout, but can produce parts in high volumes. A diagram of a flow shop can be seen in Figure 1.2.

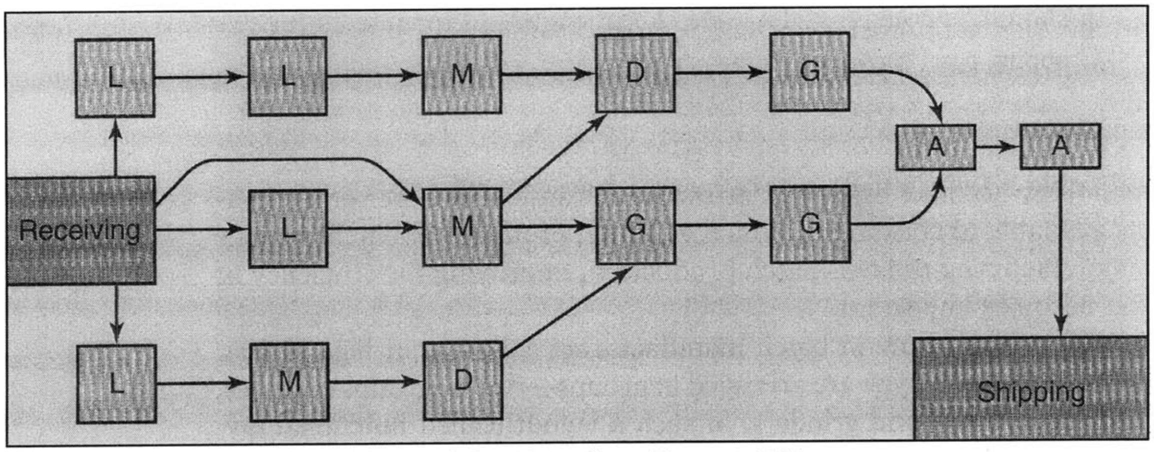

Figure 1.2: Flow shop diagram [9].

1.2.2 Job Shop

In a job shop, the flow of material through the working area is part-dependent. In a job shop, different types of machine are grouped together (milling machines in one area of the shop, grinding machines in another, etc.). The path each part takes through the shop depends purely on the operations required to machine the features on the part. This makes job shops flexible and able to manufacture lots of different types of parts without significant re-arrangement of machine tools, but also limits a job shop to producing smaller volumes of parts than can a flow shop. A flow shop diagram is depicted in Figure 1.3.

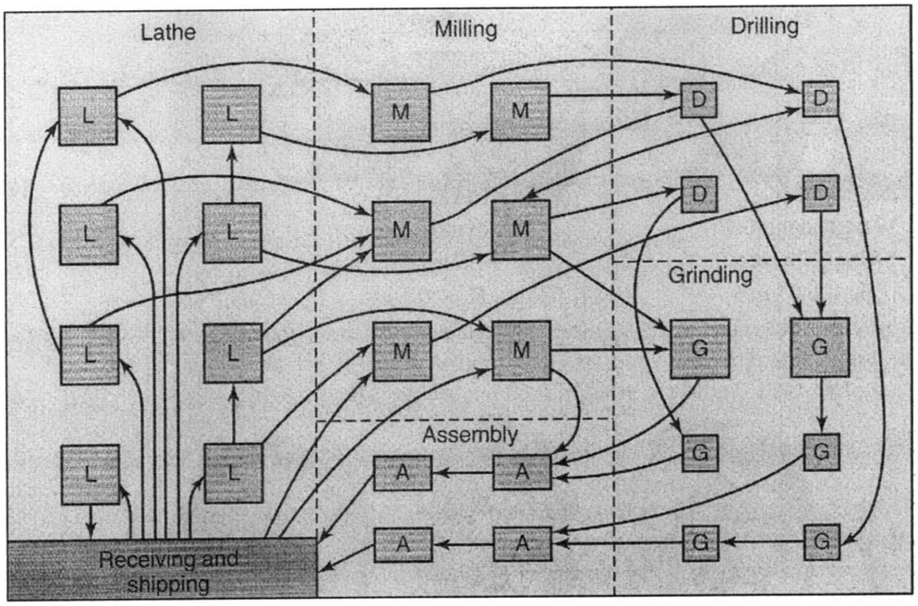

Figure 1.3: Job shop diagram [9].

1.2.3 Machining Cell

A machining cell is composed of all of the different machines required to make a certain part, arranged with respect to the order in which features on the part are created. This make machining cells relatively flexible, but not as flexible as a job shop, yet able to produce parts in a higher volume than a job shop because of the more ordered arrangement of machines and the lower feature variability from part to part. Figure 1.4 shows a schematic diagram with the characteristic layout of a machining cell.

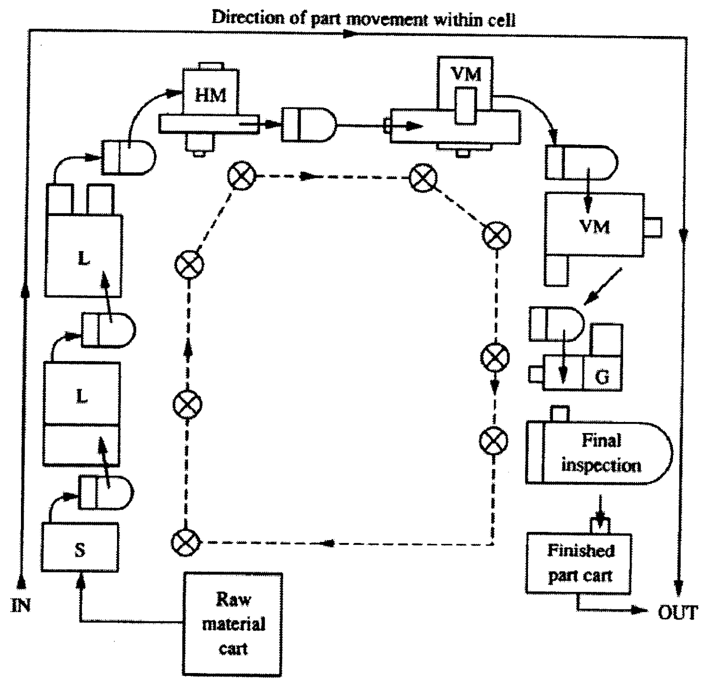

Figure 1.4: Machining cell diagram [10}.

1.2.4 Manufacturing Equipment and Machine Tools

Modern manufacturing tools have come a long way since 1830, when Henry Maudsley designed and constructed an enormous lathe in his shop in Lambeth, London, England. The lathe's face plate was 9 feet in diameter and it operated above a 20 foot deep pit. Its uses varied from turning flywheel rims to boring 10-foot diameter steam cylinders [10]. This is an excellent example of "macro" machine tools that have been in use over the past several centuries and have shaped the course of society. The characteristic sizes of these machine tools are on the order of feet to tens of feet. Parts produced by these machines generally range in size from on the order of inches, to tens of feet.

Along with these macro machines came new discoveries regarding the structure of materials: the grain structure of steel and how it could be altered through heat treating thus determined its hardness and its "machine-ability"; the perfection of aluminum smelting; the development of materials like workable materials like titanium, and materials for tooling like silicon-carbide. The development of more advanced and precise machine tools than Mr. Maudsley's lathe were, generally, guided by advancements in characterizing chip formation and refinements of cutting theory. A set of simple guidelines served to indicate whether a process carried out by a machine would produce high cutting forces, give a good surface finish, or be able to meet dimensional tolerances. These in turn led to refinement of the "best" geometrical and topological layouts for the machine tool.

In "macro"-machining, the tool is several times larger than even the largest grains found in the material being cut. Chip formation and cutting force have been empirically modeled and closed-form equations are available to the machinist to allow for the optimal feeds and speeds to be used in a given operation. In the case of micro and nano-machining, the size of the tool might be on the same order of size of the grains of the material; additionally, some types of micro and nano-machining do not even have a tool, and rely specifically on either the delivery of materials or energy to the workpiece.

Some of the most common operations performed in the machining industry include turning, cutting, and end-milling. All three of these operations are used in the creation of macro-scale parts. Some micro and nano-machining processes are already being used, and have been used for the past few decades) to mass-produce products. These include the lithographic processes used to create integrated circuits on silicone wafers. The basics physics of macro-scale machining (in terms of turning, cutting, and end-milling) do not carry over to the nano-scale. While body and gravitational forces dominate on the macro-scale, intermolecular and inter-atomic forces dominate on the nano-scale. As such, choosing a manufacturing system to enable or with which to integrate a specific micro or nano-machining operation into is not as simple as choosing the most similar macro-machining operation.

1.3 Manufacturing Processes

A manufacturing *process* is different from a manufacturing *system* in that the latter is made up of one or more of the former, and utilizes them to make a product. Manufacturing systems seek to combine and take advantage of several manufacturing processes modifying a work-piece (or pieces) in various stages of completeness. Manufacturing processes can also be classified similarly to manufacturing systems. Here, the goal is to give a brief overview of the most general processes, and the variables, rules, and guidelines used to fully describe and govern each of them. It is then assumed that any sub-process to those addressed here would also be fully described.

For example: Welding, as a general process, involves mechanically joining two pieces of material together on a molecular level. Tungsten Inert Gas (TIG) and Arc welding are both sub-types for joining metals, and vibration welding is used to join plastics and other polymers. While welding as a general process can be described by a certain set of variables and guidelines, so can TIG, Arc and vibration welding by the same basic sets of variables and guidelines.

1.3.1 Manufacturing Variables

The manufacturing systems presented above are each the result of the work of generations of manufacturing engineers. Gutowski describes 6 manufacturing variables including time, rate, cost, quality, flexibility and the environment. Time refers to variables such as customer, manufacturing, and factory lead times, and while essential to describing the manufacturing operation as a whole, the focus of this thesis is on the design of nanomanufacturing machines so detailed consideration of these variables is non-essential. Time is also described by Gutowski as "machine process time", and for simplicity here it is lumped in with rate [12]. Superposition applies here: the variables which describe machines which enable (nano-)manufacturing processes can be summed when determining the characteristics of the manufacturing system in which they are utilized. The 5 variables presented as follows can be used to accurately describe the performance of a machine or process :

1. *Rate* (λ) – the rate describes how fast the manufacturing system or process can make product, or in other words it describes the flow of product through the system. This can be measured using Little's Law $L=\lambda W$; where L is the number of units (work) in, or the inventory of the system, and W is the time the unit or work spends in the system (including time spent as inventory) [12].

2. *Cost* – describes the expenses related to operating the manufacturing system or supporting a process, as measured in dollars. Often it is estimated in terms of physical units such as machining time, units of energy, pieces of equipment, cost for materials, etc [12].

3. *Quality* – there are many different definitions of quality. Here, quality is assumed to refer to the “goodness” of the products manufactured, or as defined very eloquently by Gutowski: "quality, at the process level can be measured as the ability to hit a specific target" [12].

4. *Flexibility* – is the ability of a system or process to adapt to changes associated with all aspects of manufacturing, including other manufacturing variables. It can also be used to describe how many different products are able to be manufactured by a given manufacturing system or process [12].

5. *Environment* - describes the two-way relationship between a manufacturing system or process and it's surroundings, including but not limited to energy consumption, waste, and the production of toxic or hazardous byproducts [12]. For nanomanufacturing the units being produced could very well be toxic and/or hazardous themselves, meaning that additional thought must be put into operations like material handling.

This set of variables can be used to accurately describe the characteristics and performance of almost any manufacturing system. Figure 1.5 shows each type of manufacturing system compared in terms of a) Flexibility vs. Rate, b) Quality vs. Rate, and c) Flexibility vs. Quality, to attempt to provide the reader with further intuition regarding the characteristics of each process relative to one another.

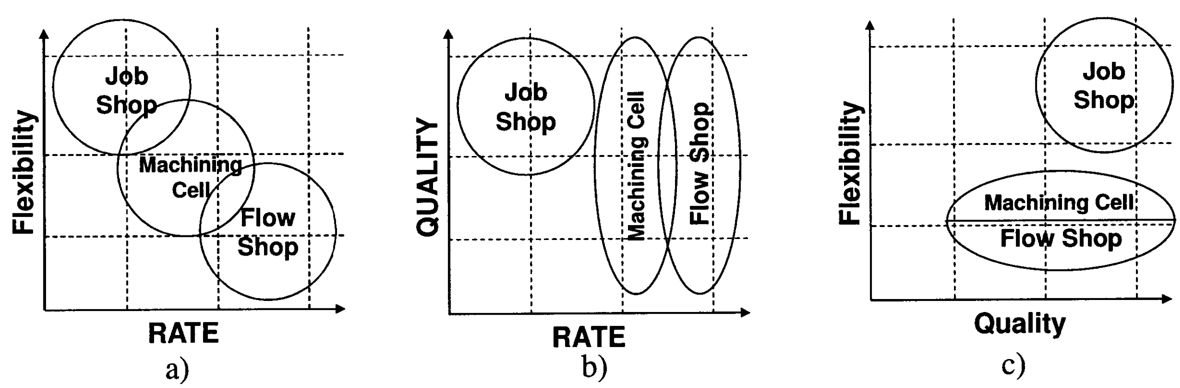

Figure 1.5: Manufacturing systems characterized with respect to rate, quality and flexibility.

Here is where the distinction is made between conventional, macro-manufacturing systems (m-mfg) and micro/nanomanufacturing systems (n-mfg). As such, and in keeping with Westheimer[1], it would seem the best choice would be to now use the knowledge of current manufacturing system technology as well as different types of nanomanufacturing processes to determine which manufacturing system is best suited for a given nanomanufacturing process. The manufacturing variables used to describe each process will then be used to recommend a specific manufacturing system be utilized or modified in order to maximize the capability of the nanomanufacturing process it is being used to enable.

1.4 Nanomanufacturing Systems

According to Lyons, " nanomanufacturing can be defined as all manufacturing activities that collectively support an approach to design, produce, control, modify, manipulate, and assemble nanometer scale objects and features for the purpose of fabricating a product or system that exploits properties seen at the nanoscale". Currently, instruments for enabling nanomanufacturing processes have satisfied the "control, modify, and manipulate" aspects of nanomanufacturing, now nanoscale products must be able to be "produced" on a large scale in order to realzie their full potential [5].

Conventional wisdom for any instrument or device suggests that in order for any process that is enabled by said instrument or device to become commercially viable, the device must be able to produce parts or products in a cost-effective manner. Over 100 years of knowledge and experience are available to a design engineer when considering integration of a machine tool enabling macro-scale processes (milling, turning, water-jet cutting) into a production/manufacturing line. Additionally, the basic technological architecture is also available on the macro-scale. Hundreds, if not thousands of plants and production lines are utilizing these technologies each day to provide our society with the products it demands.

An "instrument" cannot be used in a manufacturing system to enable a process when there is potential to design and develop a precision machine to enable that same process at a

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[1] "A couple of months in the laboratory can often save a couple of hours in the library" - Prof. Frank Westheimer.

much higher rate. A nanomanufacturing instrument must be modified to be able to be integrated into a nanomanufacturing system. This thesis seeks to identify a set of goals and guidelines to be used when transforming an instrument for fabrication of nano-scale features into a production machine for the manufacture of high volumes of products which utilize those nano-scale features.

In order to fully realize the potential of some nanomanufacturing technologies, they need to be integrated into manufacturing systems, however, instruments currently used in "nano-fabrication" processes are inherently different than their macro-scale counterparts. As a result, the full potential of many nanomanufacturing processes cannot be realized because they are not currently able to be integrated into manufacturing lines. As such, using a deterministic design process an overall machine architecture has been proposed, and a machine tool tailored to a specific nanomanufacturing process (Dip Pen Nanolithography, or DPN) has been reduced to practice, in order to verify it's efficacy at enabling DPN as a manufacturing process.

Feynman, in a speech given in 1959 at Caltech, outlined a process similar to E-beam lithography, which could be used to print the entire Encyclopedia Britannica on the head of a pin [13]. This is one of the first documented discussions regarding "nano-technology", a term that wasn't coined until several decades later. Budworth [14] and Chryssolouris [5] highlight the potential impact nanomanufacturing can have on society if successfully utilized to enable the mass-production of nano-technology-based devices. Given the current small-scale methods used to execute these processes, it is absolutely necessary to design equipment to satisfy the needs of nanomanufacturing processes. The technology required to enable nanomanufacturing processes to produce on a far larger scale than at present is essential to harnessing the true potential of nano-technology. The goal of this thesis is to provide scientists and engineers with a Lego™-like (normal or duplo) building block, to be utilized to help realize the full potential of nanomanufacturing processes.

As stated earlier, it would be wise to attempt to learn from history, and in some way draw parallels between certain nanomanufacturing processes and their macro-scale counterparts. In order to do this, the PUGH chart in Figure 1.6 can be used with the same manufacturing variables on the horizontal axis, but with different manufacturing process on the vertical axis. If a nanomanufacturing process and "macro"-manufacturing process (a macro-scale process that is currently used in a manufacturing system) were to obtain similar scores in the Pugh chart, then the manufacturing system used to enable the macro process would be the first type considered to enable the nano process. Using this method, a Pugh chart can be used to objectively identify similarities and create parallels between nano- and macro-manufacturing processes, and thus help in choosing the best manufacturing system for a given nanomanufacturing method.

1.4.1 Nanomanufacturing Processes

The different types of nanomanufacturing processes are as far-reaching and varied as their macro counterparts. They all cannot be described in detail within the scope of this thesis; it would be optimal to present the most common, well-known and well-developed processes to give the reader a good idea as to the range of nanomanufacturing processes that are available. As such, the entirety of Chapter 2 is devoted to nanomanufacturing processes. It describes several in detail, gives examples of their uses, and also provides references for other processes.

1.4.2 Nanomanufacturing Variables

Chryssolouris *et al.* stated that "The general four classes of manufacturing attributes, cost, time [or rate], quality, and flexibility … have to apply to nanomanufacturing aspects and can contribute to the optimization of every nano-oriented industrial level process so as to receive the expected results" [5]. While these four manufacturing variables form the basis for describing and analyzing manufacturing processes and systems in general, they must be expanded upon in order to accurately describe nanomanufacturing processes. These variables must include parameters which describe the physics of the process, its sensitivity to typical disturbances encountered in a manufacturing setting, and the potential negative impact that nano-structures could have on the surrounding environment [14]. As an example, when a part that has a characteristic dimension of 20 cm is being machined, it is sometimes acceptable to have errors on the order of microns. In a nanomanufacturing process however, the parts can have characteristic dimensions *on the order of 20 microns*, and thus micron-level errors will result in dramatic (even catastrophic) variations from part to part for the nano-process.

While these new parameters are not critical to matching a manufacturing system to a process, they are addressed and included here to stress the importance of not losing sight of them after the system has been selected; they *are* critical to the design of the nanomanufacturing machine. These processes are: feature resolution, alignment accuracy, and environmental impact

[15]. Here, the environmental impact is bi-directional, referring to the sensitivity of certain nanomanufacturing processes to their environments (necessitating clean-rooms, temperature and humidity control, etc.), as well as potential problems associated with nano- and micro-scale products being released into the environment that could be harmful to surrounding ecosystems and human populations.

The parameters which are critical to matching a nanomanufacturing method to its "best process" are the rate, cost, quality, and flexibility. Additionally, the energy, feature resolution, alignment accuracy, and environmental impact also factor into the equation, but are not addressed here for simplicity. These variables are presented in the PUGH chart seen in Figure 1.6. The manufacturing processes off of which to base the design of new nanomanufacturing equipment can be determined using the metric-mapping process outline in Chapter 3.

	Rate	Quality	Flexibility	Energy	Cost	Feature Resolution	Alignment Accuracy	Environmental Impact	
Job Shop	-1	+1	+1	-1	-1	-	-	-	
Machining Cell	0	0	0	0	0	-	-	-	
Flow Shop	+1	0	-1	+1	+1	-	-	-	

Figure 1.6: PUGH chart comparing manufacturing systems to process parameters.

1.4.3 Metric Mapping for Conventional Processes

How does a design engineer create nanomanufacturing equipment? Is using a deterministic design process [16] enough to ensure that the final design is adequate and will meet the requirements of the nanomanufacturing process? There must be some inclusion of the history of manufacturing: what has been done before, what has worked well and what didn't work (or failed catastrophically). Simply listing references for design analysis and design parameters, while they are important to the design process, does not adequately address the relationship between what has been proven to be effective in manufacturing and what is needed to enable nanomanufacturing

Manufacturing is manufacturing, whether it be conventional, micro, or nanomanufacturing. Relating different "flavors" of manufacturing together can be done in a variety of ways. For example, consider additive (3-D printing) and subtractive (end-milling) processes as two different types of conventional manufacturing: they are characterized based on the way in which the atoms in the end product are manipulated prior to achieving their final location within the part. Still another process is forging, where material isn't so much as removed or added as it is smashed and molded into a new shape. What are the analogous nano-processes? Dip Pen Nanolithography (DPN) can be considered an analogue to 3-D printing, while nano-EDM can be considered the nano-scale cousin of end-milling.

The question here is, how do you *prove* that DPN is the nano-scale analogue to 3-D printing. 3-D printing is not yet a viable method of manufacturing things on a large scale, so how would a design engineer go about designing a machine to enable DPN on a large-scale? A method for drawing parallels between a nanomanufacturing process and similar macro-manufacturing processes would be helpful in guiding a design engineer through the first steps. The design engineer's own ingenuity and creativity can then be used to modify and adjust the method as needed.

1.4.4 Instruments for Nanomanufacturing

Instruments for nanomanufacturing are currently available, and are capable of implementing a given nanomanufacturing process in the laboratory. Consider the following examples of an instrument for nanomanufacturing (the NanoInk NScriptor™) and a machine-tool for a nanomanufacturing process which is similar to it's macro-scale counterpart, the Sodick AE05 Nano EDM machine, as seen in Figure 1.7.

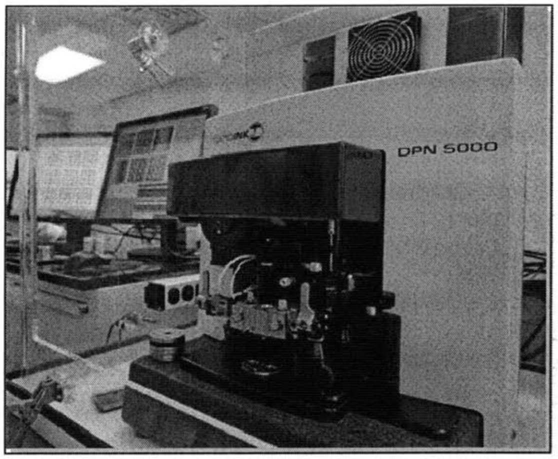

Figure 1.7: a) NanoInk NScriptor™ DPN® system [17]; b) Sodick AE05 Nano EDM machine [18].

The NanoInk NScriptor is an example of an instrument which has been designed with the focus of enabling the nanomanufacturing process in mind, with little consideration given to how integration of a machine into a manufacturing line would be achieved. The NScriptor™ system suffers from high set-up (or cycle) time, on the order of 20 to 30 minutes; it is a scientific instrument, not a machine tool. Tthe Sodick Nano EDM machine, on the other hand, looks similar to vertical machining centers produced by companies like Haas [19] and Mazaak [20], each with a reputation for producing some of the world's best precision CNC machine tools. Nano-EDM is also similar to it's macro-scale counterpart; currently available technologies such as the Belmont Maxicut™ EDM machine seen in Figure 1.8 are evidence that certain nanomanufacturing technologies have begun to move to the factory floor.

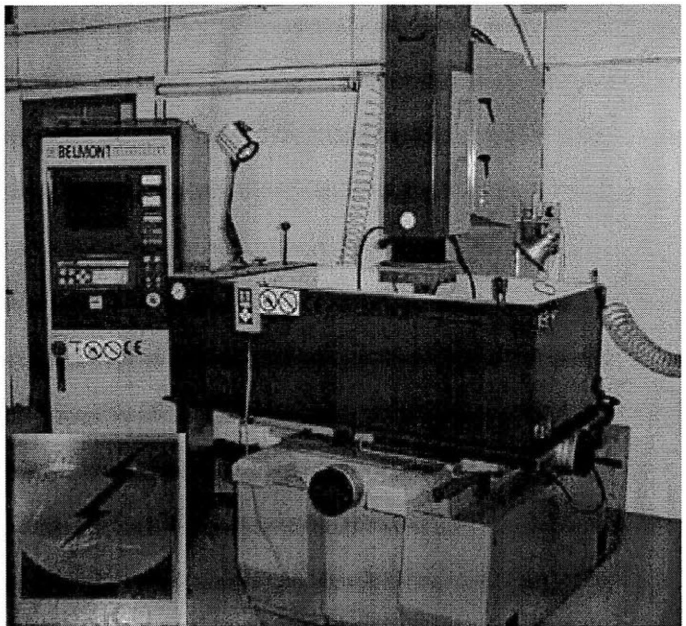

Figure 1.8: Belmont Maxicut™ EDM Machine [21].

It might be intuitively obvious (with a quick look through the latest manufacturing technology catalog) to the more experienced manufacturing engineer which types of macro-manufacturing technology would be useful in integrating the Sodick AE05 nano-EDM machine into a manufacturing line. However, without detailed knowledge of the nano-EDM process, things like environmental controls or workpiece handling and positioning requirements, meeting the technological needs of nano-EDM as a process in a manufacturing environment can prove difficult.

Furthermore, given that the NanoInk NScriptor™ is still a scientific instrument, it is a non-trivial task to determine the optimal machine architecture and layout of material handling structures for enabling DPN. The best practices for integration of DPN machines into a production line are also unknown, and these are questions which are not easily answered from a catalog, or even a comprehensive manual on machine design. In order to answer these question it would require the manufacturing or design engineer to design and implement new technology to meet the unique needs of DPN as a nanomanufacturing process.

Instead of attempting to retro-fit or modify currently available technology, the design process will be followed from the beginning with functional requirements developed from the process characteristics. Starting anew and focusing on designing a new machine (or machine architecture as is done in this Thesis) will not only yield a piece of manufacturing equipment designed specifically for the process (whether it be DPN, Nano-EDM, etc.), but will also encourage and enable a design engineer to learn a design methodology for designing equipment for nanomanufacturing. The long-term benefits are apparent in that a method can be repeatedly applied to multiple different nanomanufacturing processes, and can be used by others to help them efficiently and effectively design their own nanomanufacturing machines.

1.4.5 Nanomanufacturing Equipment

There is a difference between a scientific instrument for enabling a nanomanufacturing process, and a piece of manufacturing equipment utilized to perform a nanomanufacturing process. The former is usually developed in a laboratory setting, where the goal is to perfect a certain process, or study its characteristics and other aspects of the process. The latter is the result of a demand or need for large quantities of the product created by the process enabled by the instrument. Nanotechnology has huge potential [5, 13, 14], but in order to reach that potential, there must be manufacturing systems available which can support the creation of enough product so as to meet demand, which is not possible using an instrument.

In order to quantify and elucidate the differences between instruments and manufacturing equipment for enabling nanomanufacturing processes, and to identify what must be done in order to transform an instrument used to enable a nanomanufacturing process into a nanomanufacturing machine, a method will be presented which will allow for both a quantitative and qualitative comparison of the characteristics of different conventional manufacturing processes with a specific nanomanufacturing process; the end goal being to use conventional manufacturing technology as a starting point for the development of nanomanufacturing technology.

Any manufacturing machine, including nanomanufacturing machines, must be designed with physical characteristics of the manufacturing process in mind, like necessary throughput to keep the process economical, the workpiece handling machinery, and waste disposal. Furthermore, the physical limits of the machine (in addition to things like positional accuracy and thermal sensitivity), as expressed in terms of Mean Time To Failure (MTTF), and Mean Time to Repair (MTTR), place restrictions on which types of machine elements are best suited for incorporation into the machine. For example, a machine which moves a large mass at high velocity in order to keep throughput high, must be designed to be stiff, mitigate vibrations, and also have small thermal drift in order to meet the demands of a manufacturing environment.

Mean Time to Failure is described by Gershwin [22] as the "average duration of an up period", where "up" period is the time the machine spends working and producing materials. Mean Time to Repair is the average duration of the time that the machine spends down while waiting to be repaired. While both of these should be factored into calculations of a machine's rate of production, the level of detail required to give this calculation justice is outside the scope of this thesis.

An instrument has little to none of these restrictions, as down-time for an instrument does not always mean that money is being lost, as is usually the case with a manufacturing machine. A good analogy to highlight the differences between a nanomanufacturing machine and an instrument for enabling a nanomanufacturing process would be to think of the nanomanufacturing machine as a car which must drive from one side of the United States to the other in a given period (to meet the needs of a customer on the opposite coast), while the nanomanufacturing instrument can be likened to a stock car competing in a NASCAR race. While both must be high-performance, precision machines, the former can be serviced only when it is convenient and the resources are available to do so, must operate for long periods without interruption, and can be driven in a sufficient manner (to maximize profit) by a wide range of people. The stock car, on the other hand, can be serviced at the convenience of the operator, any problems can be addressed almost immediately, and the stock car requires a high degree of skill and expertise to operate successfully.

1.5 Scope

The goal of this thesis is to highlight the fact that nanomanufacturing is in its infancy, and that parallels can be drawn between conventional manufacturing and nanomanufacturing to catalyze the development of the technology required to support nanomanufacturing processes. Also, this thesis can be used to help educate the reader about what can be learned from the history of conventional manufacturing. A basic knowledge and understanding of manufacturing systems (Chapter 1), nanomanufacturing processes (Chapter 2), and a metric-mapping methodology for developing nanomanufacturing systems based off of conventional manufacturing systems (Chapters 3 and 4) can be obtained from reading this thesis. Chapter 4 is also a case study which highlights the efficacy of the methodology presented in Chapter 3, and the design of the resulting machine architecture, work-piece handling and material processing equipment is described in detail in Chapter 5. The use of the machine to perform a nanomanufacturing process will be demonstrated and areas for improvement or other uses of the method and machine architecture will be discussed (Chapter 6).

CHAPTER

2

NANOMANUFACTURING

2.1 Opportunities in Nanomanufacturing

Instruments cannot be used in manufacturing systems when the product of that system is primarily the result of an operation performed by that instrument[2]. The need for a nanomanufacturing machine begins first with the conception of a nanomanufacturing process. Once any process has been realized and demonstrated to be utilitarian in nature, in order for it to be implemented on a large scale (and thus remain economical in a manufacturing sense) technology must be developed to support the process. The process must be implemented with high-throughput in mind; nanomanufacturing processes suffer from the fact that their output product is physically small (hence the "nano"), and therefore must produce large quantities of product in order to meet the requirements of commercialization.

When considering a nanomanufacturing process that is implemented in the laboratory on an instrument, it is important to realize that in order to be commercially viable, the instrument must be modified to integrate into a manufacturing system. Manufacturing technology that is currently used for large-scale (in the physical, bulk sense of the word) manufacturing must be modified to be able to integrate with a nanomanufacturing system. It is the goal of this thesis to identify a set of design rules and guidelines to be used when transmogrifying an "instrument" for

[2] One example of instruments utilized in manufacturing systems today are x-ray scanners used to look for cracks in high-performance metal components; they are used for analysis, and their use can be controlled for with accurate process control

creating nano-scale features into a production machine for the manufacture of a very high-volume of product utilizing those nano-scale features: a "nanomanufacturing machine".

With respect to the nano-instrument, it is important to remember that many new processes have been developed which have the capability to manufacture nano-scale features and structures. These instruments, however, suffer from low-throughput and are not designed to sustain the production loads seen in a manufacturing environment. The lack of appropriate nanomanufacturing technology is not due to a lack of demand, rather it is a lack of knowledge of how to develop a fundamentally new field of manufacturing focused entirely on the nano-world.

Opportunities in nanomanufacturing exist to design new machines based off of instruments currently used to create nano-scale features in laboratories, whereas a nanomanufacturing machine creates those same nano-scale features on a far more massive scale. Design of these machines will also take advantage of opportunities for improvement in areas which are essential to characterizing any manufacturing process: cost, quality, rate (throughput), and flexibility.

2.1.1 Rate

Rate, or the throughput of a manufacturing system, can have several different units, and in conventional manufacturing can be taken as the cycle time of the slowest machine in the manufacturing system (if there are multiple machines), or the rate at which parts or finished components are produced from the system as a whole. Gutowski describes the rate of a manufacturing system using Little's Law, seen in :

$$L=\lambda W \qquad (1)$$

where L is the number of units (work) in, or the inventory of the system, and W is the time the unit or work spends in the system (including time spent as inventory) [12]. With regards to nano-processes, expressing the rate in terms of how quickly individual parts/components are produced is often not practical because of the small physical size of the components, and also because of the sheer volume (in terms of quantity of product).

Most nanomanufacturing processes in use today suffer from low throughput, and thus are not suitable in their current embodiment to be integrated with a manufacturing system. In order to be economically and physically viable for mass-production of nano-structures and nano-materials would require that new technologies be developed to enable high-throughput applications for each of these nano-processes. For example, scanning-based nanomanufacturing methods are naturally low-rate; in order to transform a scanning-based process which has already been perfected in the laboratory, into a high-throughput nanomanufacturing method, would require the development of new technology designed specifically for enabling that specific process. The focus of this thesis is on the development of that new enabling technology, and the deterministic process a nanomanufacturing engineer would use to both synthesize new technology and modified manufacturing technology using prior art as a reference.

Another means of increasing the throughput of a nanomanufacturing process is parallelization, and an excellent example of this is Dip Pen Nanolithography, discussed in section 2.4.1.1. In essence, the attempt to increase the cycle yield by using an array of tips causes a single-axis alignment/offset problem to become a six-axis alignment problem. This highlights the sensitivity of throughput for template-based processes to set-up and material handling time. The actual processing time is a less critical factor. As such, in order to yield the greatest improvement in machine performance, developmental efforts should be focused on the creation of new equipments to enable nano-mfg processes focused on improving throughput.

2.1.2 Cost

The goal of almost every manufacturing operation is to reduce cost. The Toyota production system (TPS), flexible manufacturing, and the ford system of assembly lines were all created to meet the needs of the customer. Whether it was a car for the everyman (Ford), or just-in-time delivery of product (TPS), these deliverables were all driven by one thing: money. If money were not an issue in manufacturing, there would be no need for this thesis.

2.1.3 Quality

When designing machines for enabling nanomanufacturing process, one must consider the fact that any nano process inherently requires a higher-than-normal degree of control over the dimensional accuracy of the machine. As with any precision machine, a design engineer must be cognizant of the tolerances of the process implemented by the machine, as well as the uncertainties inherent in the process which make it difficult to achieve high quality product, even with a very precise machine. The effects of these uncertainties can be mitigated or counteracted through the development of a process model, which allows design engineers to identify the critical process parameters. In designing precision machines for enabling nanomanufacturing, choosing which process parameters a machine is able to control is essential to its performance. Other elements of a typical manufacturing system, such as workpiece handling and tool positioning mechanisms must be made to achieve the required kinetic and kinematic accuracy defined by the process being implemented. Nano-scale metrology is also important to ensuring that the highest possible quality parts are produced.

2.1.4 Flexibility

While many nano-scale processes have been perfected (see section 2.4), as with any manufacturing process there remains the possibility for improvements or changes to be made which could affect the critical process parameters, and thus change the optimal machine layout, architecture, or best technology for operations like work-piece handling or metrology. Any piece of nanomanufacturing equipment should be analogous to building with Legos™. A scientist working on developing a new nanomanufacturing process, or a seasoned manufacturing engineer plying their knowledge in a new, similar-but-different field should have the tools available to them to customize as many of the features of the machine as possible.

With this in mind, it should be noted that trying to accommodate every possible configuration would result in such a complex system that it would be impossible to work with, the goal of this thesis is to put forth an idea for a modular, highly-flexible and customizable nanomanufacturing machine which can be used individually or expanded into a manufacturing line. Furthermore, the development of a method which can be used to map certain macro-manufacturing processes to their nano-scale counterparts provides scientists and engineers with a tool which can be used to help them achieve their goals in developing nanomanufacturing equipment, or confirm what they already know about how they are going about fabricating said technology.

2.1.5 Low cost equipment

The operation of machine tools that perform operations on the nano-scale in a manufacturing environment impose high-precision requirements, which can become very expensive. The more "0"s there are after the decimal place, the more "0"s there are in associated cost. Current practice is to modify existing technology to attempt to meet the needs of nanomanufacturing processes. The workstation cost vs. the rate at which the workstation processes surface area for currently available technology for enabling nanomanufacturing processes is shown in Figure 2.1 [23].

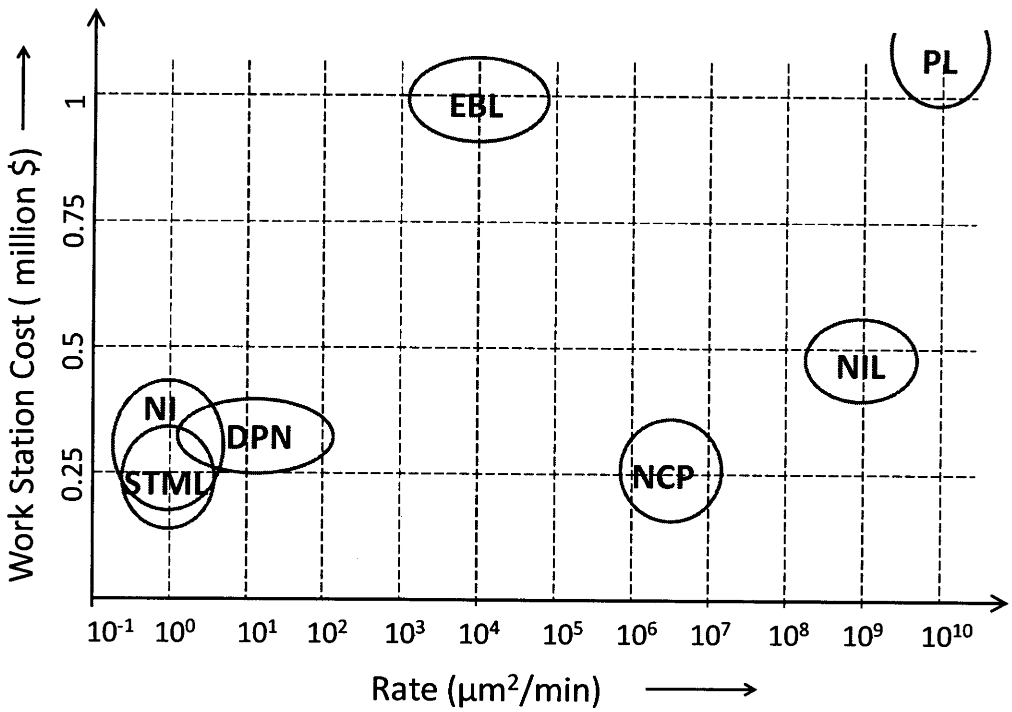

Figure 2.1: Workstation cost vs. area processing rate for Dip Pen (DPN), Scanning tunneling microscopy lithography (STML), Nano-indentation (NI), E-beam Lithography (EBL), Nano-Imprint Lithography (NIL), Nanocontact Printing (NCP), and Photolithography (PL) [23].

What is currently available for certain aspects of the manufacturing process such as workpiece handling and metrology systems is inadequate because the rate describes how fast the manufacturing system or process can make product, or in other words it describes the flow of product through the system. This can be measured using Little's Law $L=\lambda W$; where L is the number of units (work) in, or the inventory of the system, and W is the time the unit or work spends in the system (including time spent as inventory) [12]. They are tailored specifically for use in conventional manufacturing. Their accuracy and precision capabilities meet the requirements of most nanomanufacturing processes but they have yet to be integrated into the appropriate machine architectures and machine layouts geared specifically towards nanomanufacturing.

A good example here is the development of manufacturing equipment for processes like DPN, or STM-Lithography. They use existing atomic force microscopes (in the case of DPN) or scanning tunneling microscopes (in the case of STM-lithography), which are scientific instruments whose primary utility is in a laboratory setting. Figure 2.1 shows the cost of currently used processing workstations for different nanomanufacturing processes [23]. If one were to suggest that using multiple machines in parallel to increase throughput, it can be seen in the figure that on a purely cost-rate basis it is not economically feasible.

It should also be noted that while the plot is useful for performing an assessment of what is needed with regards to the development of new equipment, it does not address the full cost of implementing a nanomanufacturing process beyond that of the initial purchase of said capital equipment. The implementation of work-piece handling and transportation equipment are also necessary for any manufacturing process. Specific technologies tailored to nanomanufacturing processes currently are non-existent, providing support to the need to design new machines for enabling nanomanufacturing on more than just a cost-basis. Also, this discourages the practice of modifying existing technology to try to meet the needs of a nanomanufacturing process.

2.2 Classification of Nanomanufacturing Processes

Nanotechnology is an incredibly far-reaching, interdisciplinary field. Mechanical Engineers, Biologists, Materials Scientists, Physicists, and Electrical Engineers are all equal on the nano-scale. In both the physical and intellectual sense: all think differently, but at the same time are made up of the same types of atoms and molecules. As such, classifying various methods of implementing nanotechnology (nanomanufacturing) must be done in a manner which is broad, yet at the same time, able to make useful distinctions between various types of nanomanufacturing processes.

There are several different ways to classify nanomanufacturing processes[3]. It should be noted that while these methods are varied, their implementation results in inconsistencies Common methods of process classification include but are not limited to those presented below in Table 2.1.

[3] One of the author's lab-mates had already poured several hours into the task, and was kind enough to spend an hour with the author and review those failed attempts. This was an invaluable contribution and this thesis would have taken many more moons to complete without it.

Table 2.1: No two schemes for classifying nanomanufacturing processes are alike, and different processes could be classified differently by each method [23].

Process Descriptive Parameters	***Parameter Embodiment***
Delivery of agents	*Energy* *Materials* *Light*
Applications	*Electronics* *Biomedical* *Energy* *Defense*
Material change	*Addition* *Removal* *Constancy*

Material characteristics	*Soft*
	    Biological (cells), Organic matter (proteins, DNA)
	Hard
	    Ceramics, metals, polymers

Tool geometry and function	*Soft tools*
	    Lasers, X-rays ("soft" interactions)
	Tip-based
	    Chemical, physical, and electrostatic interactions
	Template-based
	    Physical interactions.

Pattern type	*1D*
	    Nanodots
	2D
	    Nanolines, surface traces
	2½D – Nanowires
	3D – Nanostructures, Nanorobots

Patterning method	*Pattern transfer*
	    Etching
	    Nano-imprint lithography
	Pattern generation
	    DPN
	    STM-Lithography

Nanomanufacturing method	*Surface-based*
	    Deposition Etching
	Pattern-based
	    Lithography

Agents utilized to effect change	*Agents*
	    Materials
	    Energy

	Information
	Affecting Substrate
	Geometry
	Form
	Material Properties
Processing method	*Continuous* *Batch* *Hybrid (semi-continuous)*

Nanomanufacturing processes can also be classified according to the cost of implementing the process, and even based on the approach required to make it a high-throughput process. As can be seen by the list above, the different methods of classification are many and varied. In this thesis, nanomanufacturing processes have been classified in terms of metrics, so as to highlight the similarities between nano-processes, and processes currently implemented via manufacturing. This system of classification facilitates the implementation of nano-processes in high throughput flexible nanomanufacturing systems by learning from what has been done before, and using it to make educated, informed decisions on machine architecture, performance, and function. Figure 2.2 presented some typical nano-scale machining operations organized in terms of their relative flexibility and ability to operate with high-throughput.

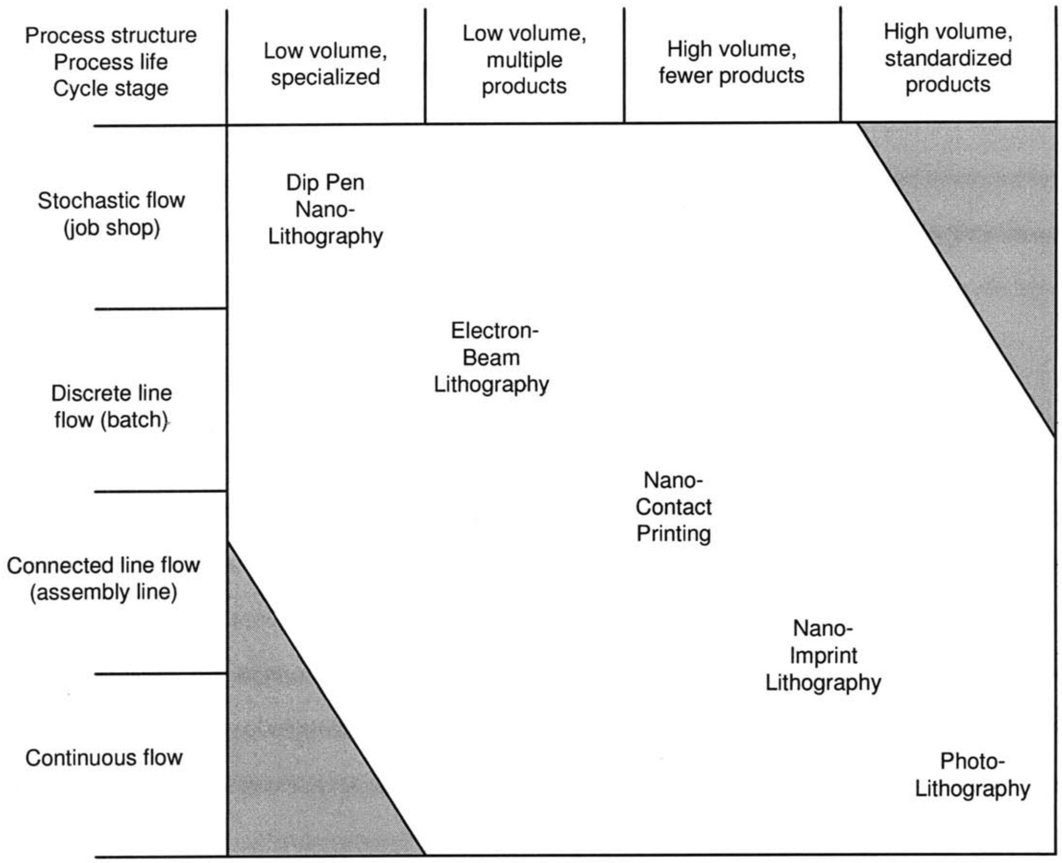

Figure 2.2: Small-scale (micro or nano) machining operations classified in terms of volume and rate vs. manufacturing system type [24].

Material processing operations can be classified into three types: material addition, material removal and material constancy. Heat treating of metals is an example of a constant material process. At the nano-scale, there are several different mechanisms that can be utilized for processing materials. For example, at the macro scale, the nature of the energy required to perform a metal cutting operation (plastic deformation) is mechanical, and can be used to modify the shape of a sample. At the nano scale, a chemical or phase change (DPN) can be used to create a focused energy transfer to create a feature on a substrate. It should be noted that the nature of the energy is thus chemical, but at the same time, mechanical energy could also have been used (Nano-imprint lithography).

Now an opportunity for technology innovation presents itself: *at the nano-scale, making one nano-feature is all but useless, thus the need to create nanomanufacturing machines*. This is exactly why nano-processes implemented using instruments are not suitable for manufacturing. Nano-technologies make up for their small scale by sheer numbers. A device utilizes nanotechnology as a surface treatment, for example, would require massive replication of a nano-feature (or features) over a large area. Even more advanced, would be a 3-D device that would require nano-features in multiple dimensions. 3-D printing is one macro-scale analog to a nano-process which could be used to make 3-D nano-structures.

2.3 Nanomanufacturing processes

According to Chryssolouris et. al, "Nanomanufacturing encompasses all processes aimed at building nano-scale (in 1D, 2D, or 3D) structures, features, devices and systems suitable for operation and/or integration, across higher dimensional scales (micro- meso- and macro-scale) aiming to provide fully functional products and useful services" [5]. What is lacking in this definition is the *technology* required to utilize a nanomanufacturing process for large-scale production of a product.

2.4 2-D Nanomanufacturing Processes

When considering a 2D process, it should be assumed that once a nano-feature has been created it must be replicated and extended over an area very large relative to the size of the individual feature. The methods capable of implementing this replication and extension can be classified into two types:

1. *Scanning-based*: the use of a tip or focused beam results in interaction with the substrate through the transfer of mass or energy.
2. *Template-based:* nano-features are transferred to the workpiece via a pre-existing template.

In a scanning-based method, replication and extension of nano-features is achieved by moving the tool tip or beam over the surface of the work-piece, resulting in large-scale transfer of energy and/or materials. In template-based methods, deformation of the substrate/surface of the workpiece is coupled to replication and extension of features. Scanning-based methods, such as Atomic-Force Microscopy (AFM) can be modified to achieve higher throughput by creating an array (a template) of multiple tips. It should also be noted that a template can be manufactured using a scanning-based method.

As an example of one of the drawbacks of classification of nano-processes without metrics, consider Dip-Pen Nanolithography. DPN utilizes an AFM tip to transfer an ink to a surface through a water meniscus; using a single tip to perform DPN would be a scanning-based process. In order to better realize DPN and achieve higher throughput, it can be implemented on a massively-parallel scale using an array of tips. The standard tip array used in this thesis contains 55,000 cantilevered dip-pen tips, thus transforming it into a hybrid process. The array of tips can be aligned to the substrate, and then drawn over it to transfer energy/materials. It can also be utilized to transfer energy/materials as a single template, thus highlighting the hybrid nature of DPN.

Another example is classifying manufacturing processes into series and parallel processes. On a macro-scale, a good example of each is the methods used to manufacture automobiles. The various components of the car are assembled in series, whereas the individual parts are manufactured in parallel to one another prior to assembly. In nanomanufacturing, utilizing a series/parallel classification system to characterize different methods would result in template-based methods being classified as parallel processes and scanning-based methods as serial processes. Consider again DPN: it has already been shown that it is a hybrid scanning/template-based process. In its implementation, the template (array of tips) is scanned over the substrate (to "ink" features), making DPN a series and parallel process.

Dip Pen nanolithography is a scanning-based process that has been discussed already, while examples of other processes include scanning tunneling microscopy lithography (STML) and mechanical nano-indentation (NI). Nanoimprint lithography (NIL) and Nanocontact printing (NCP) are examples of template based processes. Examples of parts fabricated using these processes can be seen in Figure 2.3. The tool-substrate interaction also can be used to divide scanning-based and probe-based processes into two types of processes, physical and energy-source processes. Possible energy sources include thermal, radiative, and electromagnetic energy (in the form of electron beams, thermal radiation, or lasers).

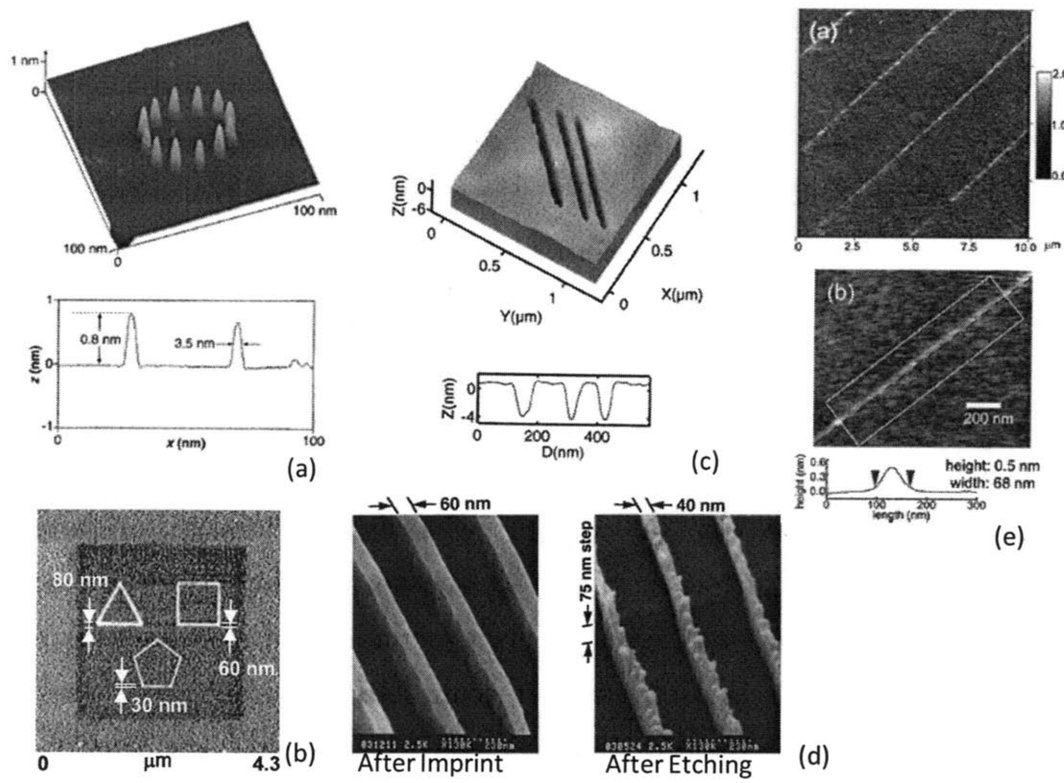

Figure 2.3: Examples of features manufactured using various nanomanufacturing processes: a) Cu deposition via STM [25]; b) Geometric thiol patterning using DPN [26]; c) 5 nm wide lines made using mechanical nano-indentation on GaSb/20nm InAs [27]; d) PMMA lines imprinted with a 75 nm step-over using nano-imprint lithography [28]; and e) Titin multimer protein lines created on the surface of a silicon substrate using nano-contact printing [29].

2.4.1 Scanning-based Nano-Mfg Processes

Scanning-based nanomanufacturing processes are very popular processes due to their flexibility and the ease with which they can be used to reliably image nano-scale features, and also to create nano-scale features through delivery of a controlled quantity of mass or energy to a substrate. A majority of scanning-based nanomanufacturing processes take advantage of a probe tip (whether it is a single tip or an array of tips) to perform the imaging or fabrication operation. Some common imaging methods include Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy (STM). Probe-based scanning processes developed using these two imaging platforms are some of the most common: Dip Pen Nanolithography (DPN) and Scanning Tunneling Microscopy Lithography (STML).

2.4.1.1 Dip Pen Nanolithography

Dip Pen Nanolithography has been called a bridge between the conventional top-down and bottom-up approaches to nanomanufacturing. It is ordered lithographic self-assembly of molecules on a substrate, delivered by an AFM tip. Also, it has been claimed that DPN (along with e-beam lithography) is "not suitable for high-rate nanomanufacturing", but is only suitable as a process for making templates (and not as an actual manufacturing process itself) by which self-assembly of different materials can be achieved [30}.

DPN is a scanning probe-based process that utilizes an AFM tip to create nano-scale features through the self-assembly of molecules on the surface of a substrate [31, 32, 33, 34, 35]. DPN uses an array of 55,000 tips to achieve massively parallel processing of substrates. However, as with most things in life, this benefit does not come without cost. The use of an array of tips turns what was originally a single-axis alignment problem (the only critical dimension being the distance from the surface of the substrate to the AFM tip used in single-tip DPN) into a 6-axis alignment problem. Parallelism of the tip array used in current technology with respect to the surface of the substrate is critical to the efficacy of the tip array in enabling massively parallel processing of DPN arrays.

The increased complexity of the tip array alignment problem provides significant opportunity for the development of technology which will allow DPN to become a viable manufacturing process. At present, a limit of the process has been reached, and existing equipment must be improved in order to achieve this goal. While the complexity of DPN can be reduced by the use of passive 2D multiple tip arrays [36], the geometric flexibility of scanning with a single-tip is lost and fabrication is restricted to non-heterogeneous periodic patterns [23].

The "writing" aspect of Dip Pen is effected by the formation of a water meniscus at the interface between the tip and the substrate. This meniscus allows the ink (or "material" as it is an additive process) on the tips of the array to "flow" onto the surface of the substrate as shown in Figure 2.4. The ink is applied to the tips via either vapor coating or by dipping the tips into a solution containing the ink. The bond between an ink molecule and the surface of the substrate ensures that the features created by the Dip Pen writing process are stable and robust; an example of such a stable interaction being the relationship between a 1-octadecane-thiol ink molecule and a gold substrate [35]. Although a variety of in-substrate combinations have been demonstrated to work with the process mechanism, DPN is still dependent on the chemical affinity between the ink and substrate [23].

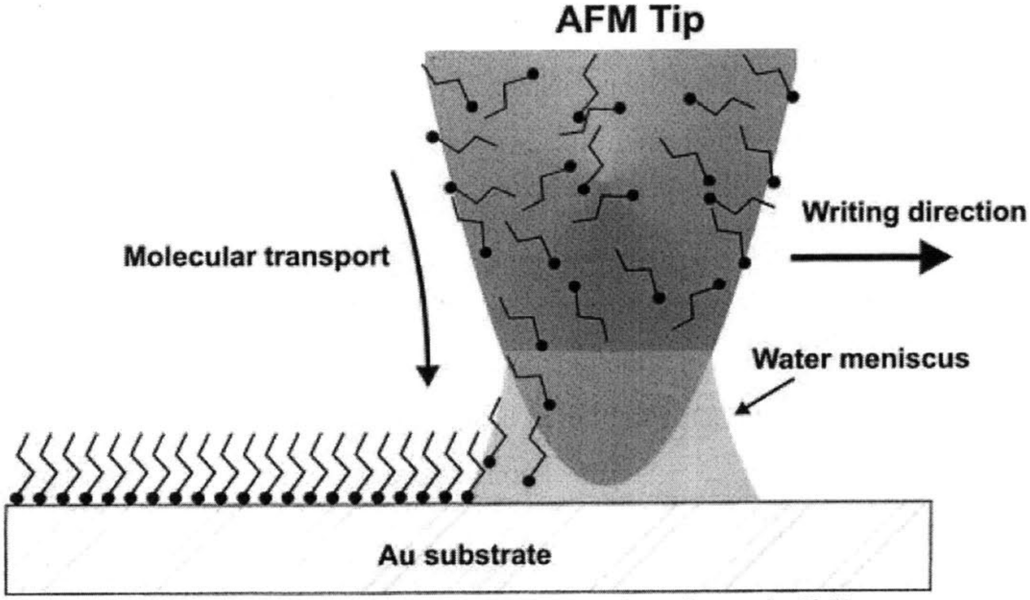

Figure 2.4: Dip Pen Nanolithography schematic [35].

For Dip Pen writing, the rate of scanning over a given area to generate features of varying sizes is constrained by the mechanism of ink flow from the tip to the substrate. As such, it is dependent on the combination of ink and substrate. For typical alkanethiol ink and gold substrate, scan speeds range from 0.1 µm/s to 1 µm/s and lead to an area coverage rate of ~0.1-10 μm^2/min [23, 34]. Features down to 14 nm have been created using Dip Pen; the repeatability of DPN has also been measured to be around 15% for features below 100 nm [33]. From working with Dip Pen Nanolithography and attempting to make improvements to the process such as increasing tip lifetime or write speed, scientists have also developed several new processes including but not limited to:

1. Thermal DPN [37].
2. Electrochemical DPN [38].
3. Nano-fountain pen lithography [39].

These process are all similar to DPN, and can be compared to spot-welding, electrochemical welding, and MIG welding. "Normal" DPN can be likened to TIG welding, with the water meniscus analogous to the argon gas used to isolate the welding process.

2.4.1.2 Micro- and Nano-EDM

Electro-Discharge Machining (EDM) is extremely useful on the macro scale because of its flexibility, as well as its capabilities at being utilized to manufacture extremely complex parts with high aspect ratios. Micro-EDM and Nano-EDM are very similar in their operation and function, save for the fact that they are utilized to manufacture parts on the micro and nano scale. Not only is the process very flexible over a wide range of length scales, it is also very useful in that it can be used to machine very hard materials; the only restriction being that those materials must be, at the very least, semiconducctive. Some materials included in this category: silicon, silicon carbide (SiC) stainless steel, titanium, and molybdenum [40].

Currently, small-scale EDM is limited by the fact that it is difficult to manufacture the thin electrode tools necessary to perform various machining operations, most important those leading to the processes flexibility and ability to machine parts with complex geometries and high aspect ratios. Benilov et al have proposed a new process to manufacture these electrode tips, namely the "Drop-off" method [40], where a water meniscus is used to effect necking in a Pt-Ir (Platinum-Iridium) blank, leading to the formation of a tool with a sharp apex only a few atoms across. Using these Pt-Ir tips, a micro EDM machine has been implemented and the viability of the EDM process when using these tips has been demonstrated. A Silicon blank was operated on using this machine, and the feature machined can be seen in Figure 2.5 [40].

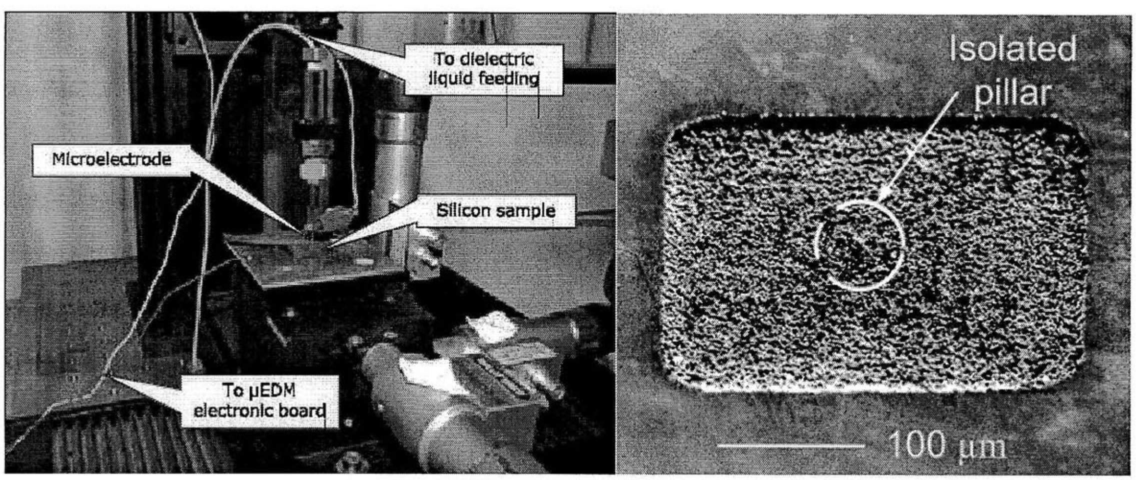

Figure 2.5: Nano-EDM machine (left) and a 250x250 µm cavity (right), with a central 1 µm diameter raised cylinder in the center, EDM-ed using Pt-Ir tips. The pocket depth was not given [40].

2.4.1.3 EBL and SBL

EBL, or Electron Beam Lithography, and Scanning Probe Lithography, are both nanomanufacturing processes which utilize electron exposure, and are capable of high resolution (on the order of 1-10 nm) patterning of organic resists. EBL is well-established, and is a technique which uses a focused beam of electrons to expose electron-sensitive resists. Albeit this process is also limited in that proximity effects cause the size of printed features to depend on local pattern density. SBL seeks to eliminate this problem by using a tip similar to an AFM probe to help focus the beam of electrons. The tip allows for the electrons to be emitted at a lower energy than in EBL, which have been suggested to eliminate these proximity effects [41].

EBL (and in turn SBL) has applications to medicine and the biosciences, as they can be used to create nano-scale features on the surfaces of organic resists. The creation of various features, such as "artificial networks of arbitrary connectivity" using these processes can be used to perform such invasive measurements as detection of inter-cellular signaling in networks of cells. Such capabilities could enable scientists to better understand the ways in which cells inside the human body communicate [42].

In Figure 2.6, an example of the proximity effects seen in Electron Beam Lithography is shown in the top image. The line spacing is 200 nanometers in both examples. One the left, a) the line width is 64 nm, and on the right, at a higher EBL dowse, b) the lines are barely resolved; the line width on the right is 120 nm. In the bottom image, 3 images are shown of different pitched gratings (in each a line-width of 65 nm is used), including a) a 500 nm pitch grating, a 200 nm pitch grating, and a 200 nm bi-directional pitch cross-hatch. The depth of each line written is approximately 300 nm [41].

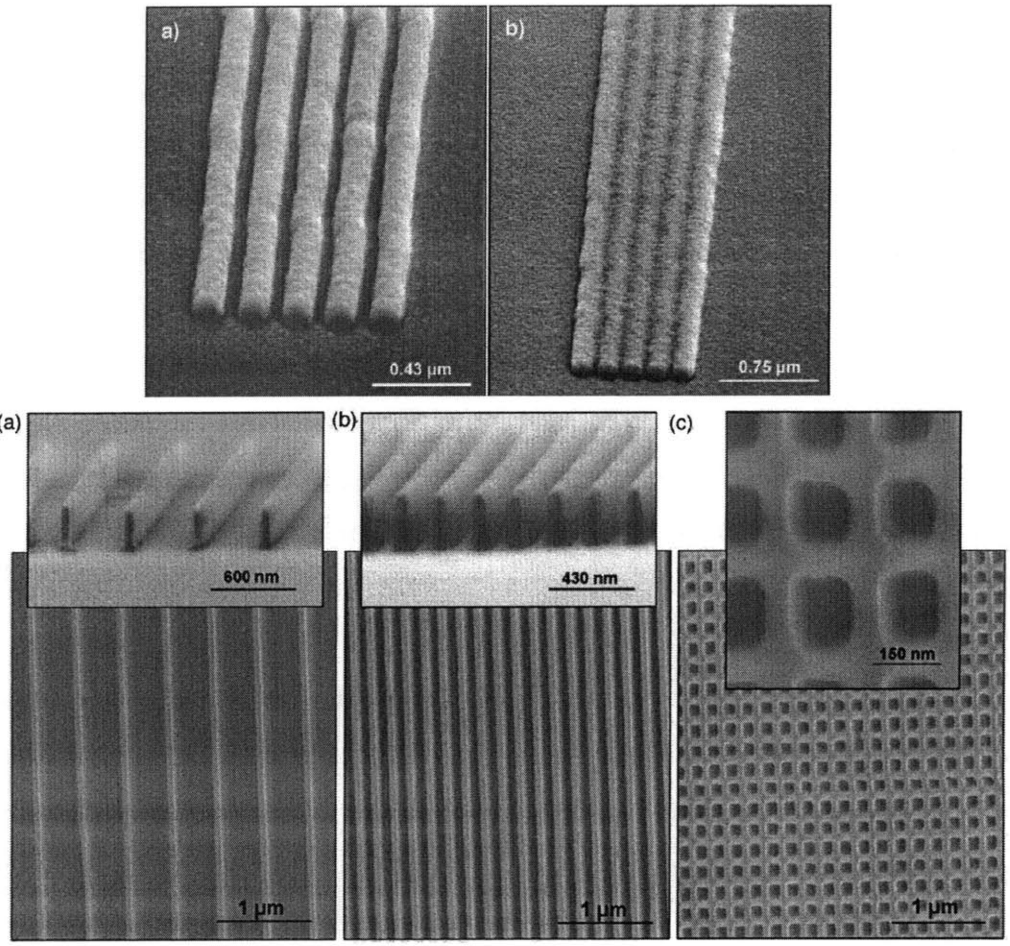

Figure 2.6: Example of EBL proximity effects (top), and gratings written using SPL (bottom) [41].

2.4.1.4 Scanning Tunneling Microscopy Lithography

In Scanning Tunneling Microscopy Lithography (STML), as in SBL, a sharp conducting tip is used to catalyze the creation of nanoscale features with resolutions on the order of the atomic scale [43]. STML utilizes the fact that electrons can be directed to "tunnel" across the interface gap, across which a voltage bias has been applied, between a very sharp conducting tip and a conducting substrate. The gap size is on the order of 1 nanometer, and the electrons are thus functionally equivalent to a focused beam as in EBL and SPL. The "beam" can be used to make modifications to the resist (changing physical properties), material additional and removal, and other manipulation operations. Furthermore, resist exposure or oxidation of a substrate is also possible using this lithographic process.

As can be seen in Figure 2.7, the electrons and tip can be used to deposit copper clusters onto a gold substrate, thus the tip has been converted into an emission source. The electrons can also be used to remove material from the substrate. Scanning rates for STML range from 0.1 μm/s to 1 μm/s, resulting in an area coverage rate ranging from 0.1 to 1 μm^2/min. In deposition mode, STML can create stable features as small as 5 nm, and features as small as 3 nm have been observed in removal mode [44, 45]. STML has also been shown by Eigler to be effective at single atom manipulation [46]. For any particular mode of deposition, the repeatability was measured at about 8% for feature sizes on the order of 20 nm [47], but this varies over a wide range due to the fact that the process mechanism is inherently dependent on the mode of operation (deposition vs. removal) and the substrate used in the process.

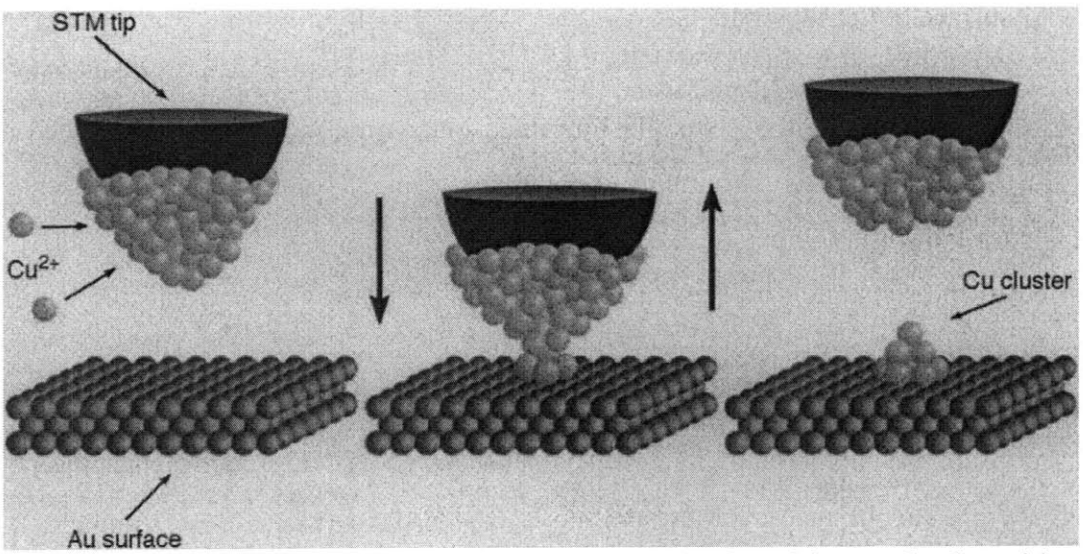

Figure 2.7: Scanning Tunneling Microscopy Lithography in deposition mode, depositing a copper cluster onto a gold substrate [25].

2.4.2 Template-based Nano-Mfg Processes

Template-based processes involve creating a pattern of nanoscale features on the surface of a substrate (or workpiece) by bringing the substrate into contact with a template tool. The tool can either containing a master pattern, such as in Nano-Imprint Lithography (NIL), or be an energy source (as in photolithography). These processes can be compared to forging, thermo-forming, and die-forming of body panels for cars, except they can be used to create features on the order of 10-100 nm.

2.4.2.1 Nano-Imprint Lithography

In Nano Imprint Lithography (NIL), as in other template-based processes, the pattern is pressed directly onto the substrate to create an imprint of the original pattern, which was achieved through deformation of the resist [48, 49, 50, 51, 52]. While NIL is a nanomanufacturing process, the patterning process can be executed on surfaces as large as a 2 inch wafer [53], making NIL a relatively high throughput process with area processing rates of a few cm^2/min [53, 54]. Nano-imprint lithography is a process which would seem to use much of the same machinery as what is used in the production of semiconductors.

Nano Imprint Lithography is a two step process that can be used to create nanoscale features, as shown in Figure 2.8. There are two steps involved in this process:

1. Substrate patterning - a mold is used to imprint the pattern onto a thermoplastic on the surface of the substrate.
2. Pattern transfer - the pattern is transferred from the polymer into the substrate.

In the first step, the pattern is generally imprinted onto a thermoplastic layer coated onto the surface of the substrate. The thermoplastic polymer is typically heated to a temperature greater than it's glass transition temperature, to ensure that it fills the mold profile when the pattern is transferred to the substrate. the substrate/mold assembly is then cooled, and they are separate from each other.

The first step in NIL results in a varying profile in the polymer layer, corresponding to the variations in the mold (or template). The second step of NIL requires that the pattern be transferred from the polymer layer into the substrate. This has been achieved through a variety of techniques for pattern transfer, for example reactive ion-etching. Using this technique, features sizes below 10 nanometers have been achieved [54, 55]. The size of the features created using NIL is limited by the size of the features on the template itself, which is usually created using EBL or focused ion beam lithography. It should be noted here that a scanning-based process is required in order to enable a template-based process. When the mold is finished it can be used for several imprinting cycles, but the limits of mold performance have not yet been sufficiently studied.

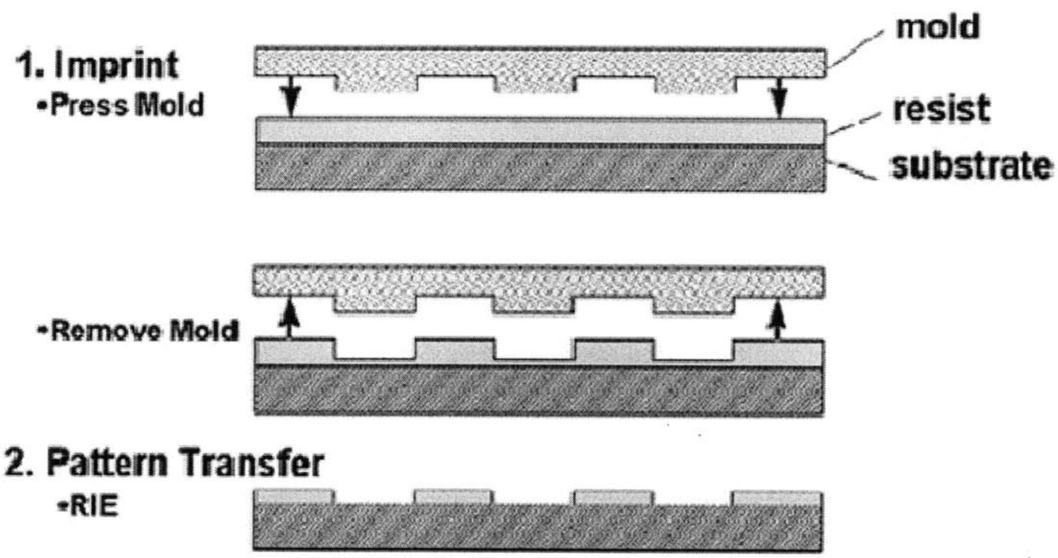

Figure 2.8: Schematic of Nano-Imprint lithography [49].

2.4.2.2 Thermolithography

Another example a template-based lithographic process that is similar to Nano-Imprint Lithography is Thermolithography, which takes advantage of the thermo-chemical cross-linking of layers of photoresist to enable modification of the substrate layer, as depicted in the schematic in Figure 2.9, which is based off of Figure 4 from [56]. The cross-linking of the polymers changes their thermal conductivity, which when the substrate is exposed to thermal treatment, often referred to as post-exposure bake (PEB), the cross-linked regions are now insoluble to a developer solution and resist further exposure to UV [56].

Thermolithography is in it's infancy, and because it is a process which utilizes a heat transfer, measuring the dynamics of those interactions are needed in order to more fully understand the develop control methods for the process. Furthermore, "lithography approaches using localized heating have been proposed... but no quantitative studies have been conducted so far due in part to limitations of the localized heating schemes employed" [56]. Further study is needed, and improvements need to be made to the process characterization methods, before thermolithography can be executed as a reliable, control-able nanomanufacturing process.

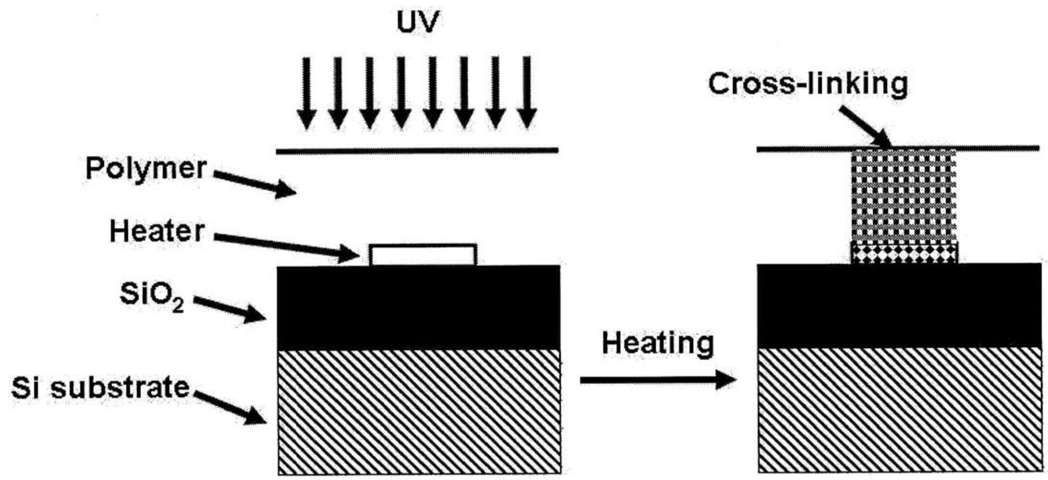

Figure 2.9: Thermolithography schematic diagram showing cross-linking in the polymer coated to the surface of a substrate, resulting in UV resistance and the creation of a pattern upon further exposure to UV [56].

2.4.2.3 Nano-Contact Printing

NCP, or Nano Contact Printing (also known as micro contact printing) is a template-based nanomanufacturing process that utilizes self assembly to create patterns [57] as can be seen in Figure 2.10. In NCP, a soft copy of the pattern is generated in the form of an elastomeric stamp, created using a process called replica molding (a process which is known to be capable of replicating features down to sizes on the order of <100 nm). After this step, the surface of the stamp is coated with an ink. As in DPN, the combinations of the ink and substrate are such that they are chosen for their chemical affinity for one another, as in the 1-octadecanthiol/gold pairing used in DPN.

The inked stamp is then applied to the surface of the substrate for a short period of time (seconds), and then the two are separated. Because the two surfaces are not atomically flat, the ink transfers from the stamp onto the substrate only where the two surfaces are in contact. This physical limitation is why it is referred to as micro contact printing, and is generally used to create features with sizes on the order of microns [58, 59, 60], however feature sizes on the order of 50 nm have also been achieved [57].. This interaction between a soft mold and a hard substrate has given rise to manufacturing processes collectively known as soft lithography [61]. One drawback here is that NCP suffers from issues of part quality due to the spread of ink along contact edges. This contamination of the contact edges results in features that are larger than the originally planned features outlined by the region of contact between the two surfaces.

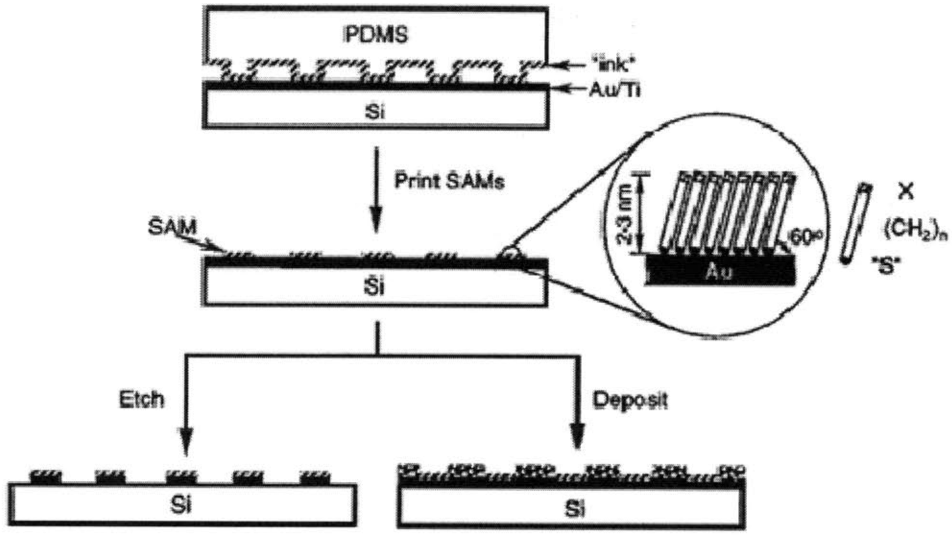

Figure 2.10: Nano-contact printing schematic [61].

2.4.3 Scanning-based Vs. Template Based Processes

The ability of probe-based methods to spatially focus the mass or energy being transferred between the tool (tip) and the work-piece (substrate) better than template-based methods makes scanning-based methods inherently more adept at creating nanoscale features. The tool/workpiece interaction places a physical limit on the size of the features that can be created, leading to the result that in general probe-based methods have a higher resolution that template based systems, as illustrated in Figure 2.11.

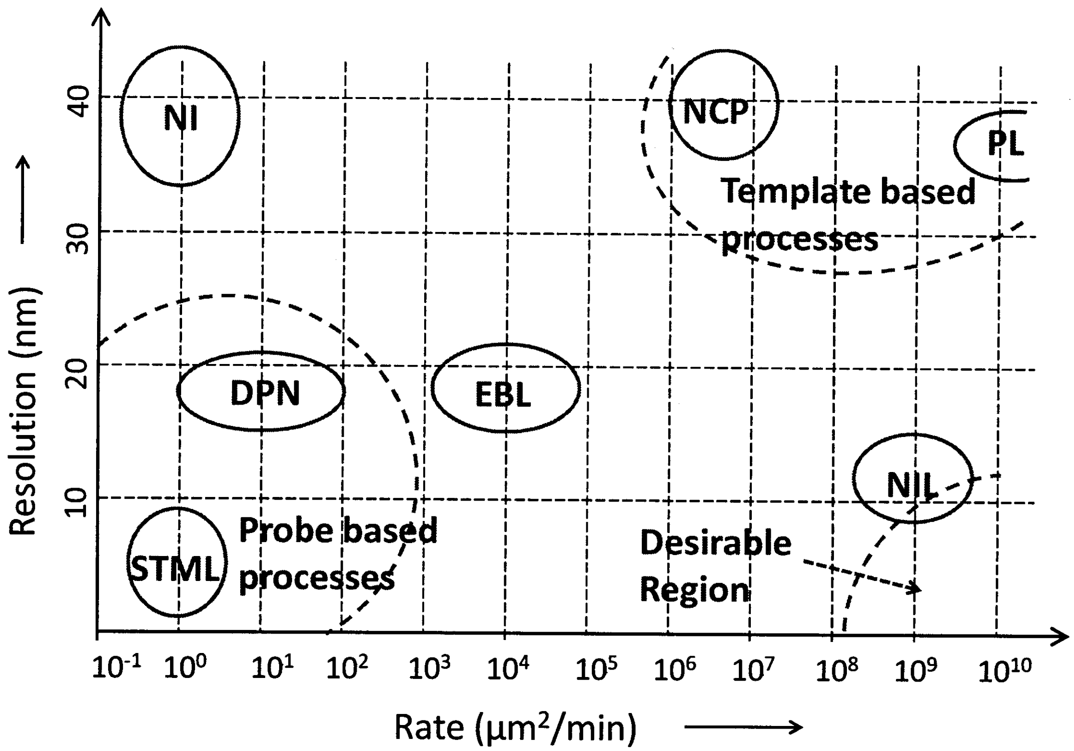

Figure 2.11: Resolution versus rate for some common nanomanufacturing processes: Dip Pen (DPN), Scanning tunneling microscopy lithography (STML), Nano-indentation (NI), E-beam Lithography (EBL), Nano-Imprint Lithography (NIL), Nanocontact Printing (NCP), and Photolithography (PL) [23].

Furthermore, scanning based methods have an inherent advantage over template-based methods: they offer greater flexibility to fabricate nanoscale features with large variations in their configuration. The macro-scale analogy here is vertical milling is a "scanning-based" process, and die-forming is a "template-based" process. The primary reason for the increased flexibility offered by scanning based nanofabrication methods is the ability to scan the tool over the surface of the workpiece (substrate). An instrument for enabling a scanning-based process would be well-suited to meet the needs of a very small-scale nanomanufacturing job shop. The high flexibility of probe-based processing methods is also a result of the fact that they can be applied to a range of different substrates, and are not limited to a specific resist material as are some template-based processes. As can be seen in Figure 2.12, probe-based processes have a unique efficacy when it comes to highly-flexible fabrication of nano-scale features.

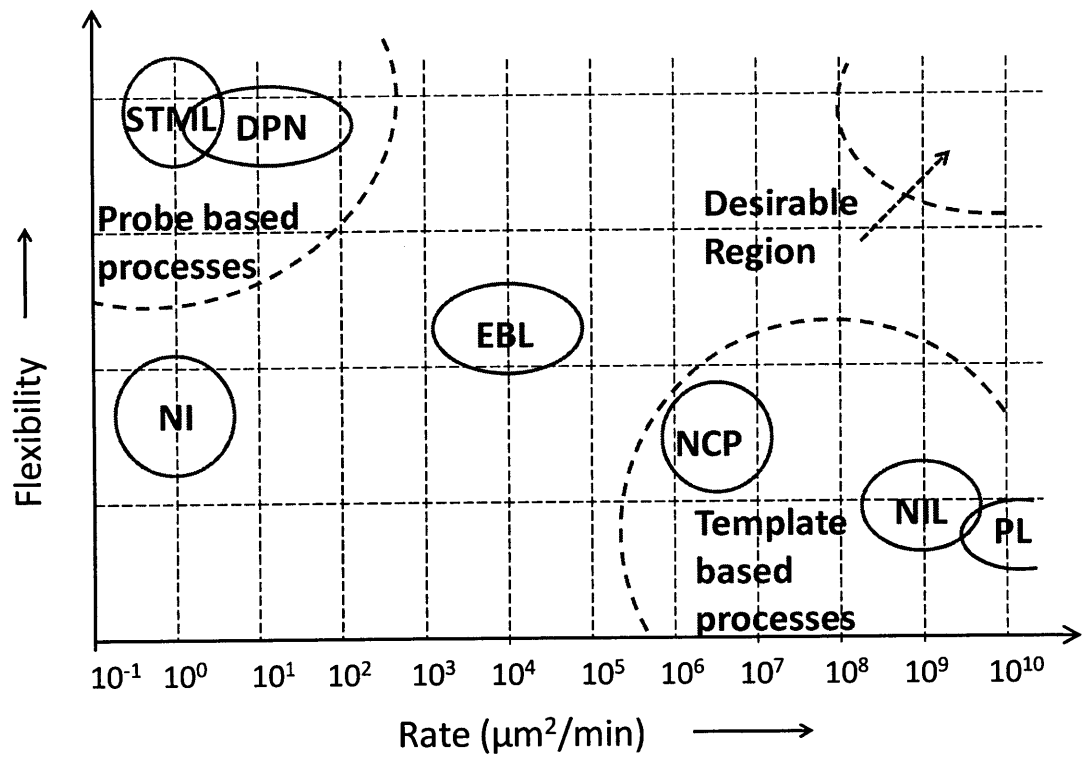

Figure 2.12: Flexibility versus rate for some common nanomanufacturing processes: Dip Pen (DPN), Scanning tunneling microscopy lithography (STML), Nano-indentation (NI), E-beam Lithography (EBL), Nano-Imprint Lithography (NIL), Nanocontact Printing (NCP), and Photolithography (PL) [23].

While these processes do exhibit high degrees of flexibility when it comes to processing different substrates and materials, what they gain from being highly flexible, they lose in overall rate of processing. The rate at which a process is carried out is highly dependent on the mechanism, and the differences in rate between a scanning-based and template-based process can be as much as 6-10 orders of magnitude for the same surface area to be processed [23]. As demonstrated in massively-parallel DPN, one way to overcome this shortcoming of scanning-based processes is to use a large number of tips simultaneously to generate a large number of patterns [36].

A massively-parallel scanning-based method moves along the rate axis of Figure 2.11, increasing rate while maintaining resolution. However, it should be noted that this is yet another trade-off: what is gained through massive-parallelization is lost through resolution and accuracy. This loss occurs unless the machine is upgraded and modified to handle what is now a six axis alignment problem created by the need for alignment between two surfaces; planarity is key to the success of a massively-parallel probe-based process implemented in such a way.

Parallelization that is achieve through the use of passive 2-D probe arrays fails to maintain the geometric flexibility of the scanning process as patterning is restricted to non-heterogeneous periodic features only [23]. Because each probe is passive, one way to overcome this loss of geometric flexibility would be for each individual probe in the array to be actuated individually. In short, a single-probe-based nanomanufacturing process can be made to overcome issues with throughput through the use of a passive array. Improvements in the accuracy, precision, and capabilities of the supporting machine architecture should be addressed in order to maintain the overall performance of the process, specifically related to alignment and positioning of the now planar tool with the surface of the workpiece (substrate).

Unlike scanning-based methods, template-based processes benefit from a high process rate due to their inherent ability to pattern nanoscale features over large areas in a single step. They are effectively massively parallel to begin with. As was shown in Figure 2.12, the throughput associated with template-based processes is higher than that of probe-based processes by several orders of magnitude [23]. Also seen in the figure is the primary drawback of those template-based processes, as demonstrated by their limited flexibility.

For a template-based process, a change in the geometry to be patterned would require the creation of a new template. This is a very slow and sometimes costly step which utilizes scanning-based processes to produce the new template. Furthermore, the material flexibility of these template-based processes is limited, as stated before. For example, in Nano Imprint Lithography and Nano Contact Printing, the process is executed through the use of a specific resist and/or ink-substrate combination [23].

This is also a problem for macro-scale processes such as die-forming. A single die could cost on the order of millions of dollars, and product hundreds of thousands of parts. Changing the die on a given machine is also a process that can be very labor intensive depending on both the size of the die and the skill with which the die must be mounted, but the loss in flexibility is more than made up for by the massive amount of essentially identical product that can be created using the die. The example of the method of manufacture for metal car bodies is brought up here again as an example of die-forming which is similar to template-based nanomanufacturing processes in terms of flexibility, throughput, and cost.

Additionally, template-based nanomanufacturing processes create two relatively large challenges for maintaining the quality of features produced by each: the ability to resolve features, and accurate alignment of the template surface with the substrate [23]. The first, the ability to resolve features using a given template results from the fact that while very high-resolution templates and patterns for template-based processes can be fabricated using scanning-based processes, it might be difficult for the template-based process to resolve all of it's features during the patterning step. This gives rise to a minimum feature size for each template-based nanomanufacturing process. The second challenge comes from the fact that no two surfaces are perfectly (atomically) smooth, and even if that is achieved, bringing two surfaces together in perfect alignment is a non-trivial problem. Furthermore, spring-back effects in the substrate upon removal of the tool, and other interactions between the tool and substrate may result in changes in the final substrate geometry. A nanomanufacturing engineer can begin to try to overcome this problem through developing a deep understanding of the process physics and incorporating functional requirements related to these challenges in the design process for a nanomanufacturing machine to enable them.

2.5 3-D Nanomanufacturing Processes

Nano-wires and nano-tubes are nano-scale products which are the result of what are called "3-D nanomanufacturing" processes [62]. These processes, however, are very specific to a given application and do not possess the inherent flexibility as other processes (such as nano-edm). One of the most ubiquitous manufacturing processes used today is actually a 3-D nanomanufacturing process. It is sometimes referred to as a 2.5D process due to the repeated use of 2-D processes to fabricate the various layers which result in the 3-D structure, the manufacturing processes in question is the fabrication of integrated circuits. While probe-based scanning nanomanufacturing methods are capable of creating different kinds of 3-D nano-features, template-based processes are not. Template-based methods can be used to create layered 3-D (or 2.5-D) structures through cycles involving application of different templates followed be exposure to UV to develop the pattern created by the template.

2.6 Nanomanufacturing Technology

It has been argued that "much of what transpires in human biology happens at the nanometer scale... [thus], all medicine is 'nanomedicine'" [63]. The distinction between "nanomedicine" and what has come before is made based on the size of the devices or tools used by physicians to interact with human biology. One such scale that has been suggested is those technology on the scale of 1-500 nm, but this needs be increased to the range from 1nm-1μm to allow for the inclusion of those nanomanufacturing processes (for example the template-based processes whose limitations were discussed in Section 2.4.3). The influence of nanotechnology could be felt in fields as different as diagnostic imaging, such as MRI, to therapeutics. In diagnostic imaging, the development of new biomarkers and imaging agents, engineered to increase the sensitivity of imaging modalities such as MRI or CT which generally suffer from insensitivity to low concentrations of such imaging agents, could increase the accuracy with which physicians could diagnose and treat disease. Furthermore, nanotechnology, and the mass-production of said technology, could also have great impact on nanotherapeutics. The ability to detect a disease early is not very useful if a treatment is not available for that disease [63].

As stated in Chapter 1, nanotechnology has huge potential to influence just about every aspect of our lives, but the applications to medicine and physiology, perhaps due to the inherent nano-scale nature of biological processes, seems to be the proverbially un-obtainable low-hanging fruit. "For applications to medicine and physiology, these materials and devices can be designed to interact with cells and tissues at a molecular (i.e., subcellular) level with a high degree of functional specificity, thus allowing a degree of integration between technology and biological systems not previously attainable". Furthermore, the nanomanufacturing industry as applied to medicine and physiology is currently in it's infancy. Most of the research associated with nanomanufacturing is at the level of basic-science (demonstrating the process). Clinical applications which are efficacious and viable for use in the general population are years away [64]. Nanotechnology also has the potential to open the doors for ultra-dense integrated circuit computers and other electronic devices that are only feasible at the nano-scale [65].

2.7 Chapter acknowledgements

I will be eternally grateful to my lab-mates for their help in writing this chapter. Sourabh Saha, Christopher DiBiasio, Michael Cullinan, and Robert Panas were all contributors to, and helped edit a review paper put forth by the Precision Compliant Systems Laboratory from which this chapter relies on heavily. Specifically, Mr. Saha compiled an incredibly detailed account of the various scanning and template-based nanomanufacturing processes for that paper, as well as detailed discussions on the benefits, limitations, and areas for improvement available to nanomanufacturing processes in use today. Also, several figures and many of the original references have been reproduced here.

CHAPTER

3

NANOMANUFACTURING TECHNOLOGY DEVELOPMENT

3.1 Metrics for (Nano)-Manufacturing

The use of metrics to classify manufacturing systems is still necessitated by the number of ways in which manufacturing systems in general (both nano- and macro-) can be described. While not as many and varied as the different species of lifeforms, the use of metrics to classify forms of life supports the use of metrics to classify the hundreds of different types of manufacturing systems which have been identified in the modern industrial environment [66].

In Chapter One, an argument was made for the benefits of using a knowledge of history to aid in designing new machine tools and new technology to enable nanomanufacturing. It is essential that individuals involved in all different phases of a nanomanufacturing enterprise have a thorough knowledge of nanomanufacturing processes [66]. In Chapter Two, several of the most common types of nanomanufacturing processes were presented. Additionally, methods for classifying both macro- and nanomanufacturing processes were shown to be many and varied, and it was stated that in this thesis nanomanufacturing process were to be classified in terms of metrics in order to be able to accurately relate and compare them to their macro-scale counterparts.

In this chapter, a metric mapping process is introduced wherein different types of manufacturing processes are compared based on sets of high and low-level metrics; the details of high and low-level metrics are discussed in sections 3.1.1 and 3.1.2. This process is not presented as the only way to go about the design and development of new technologies for enabling nanomanufacturing. Instead, the goal of this chapter is to inform others of a process that works for the development of nanomanufacturing equipment, so that they may either learn how to design new equipment, or provide further evidence towards the efficacy of their own methods.

In keeping with the historical perspectives approach, an accurate comparison needs to be made between different types of nanomanufacturing processes and conventional (or macro) manufacturing processes. In short, due to the fact that nanomanufacturing is in it's infancy, parallels can be drawn between what was done in manufacturing when it was in a similar state of technological development (e.g. when Henry Ford was developing the assembly line). As stated before, in order to be effective at improving the field of nanomanufacturing and developing automated systems for mass-producing nano-scale features, it is important that one possesses an understanding of how those processes are executed.

Once an understanding has been obtained about a nano-process, it must be compared to different macro-processes, and then the technology used by those macro-processes can be utilized as a road map for guiding and influencing the design of the nanomanufacturing machine. As shown in Chapter 2, Table 1, there are many different ways to describe a process and classify it relative to its peer processes, and each method could potentially result in a different classification. In order to be able to design machines effectively, a process must be relatively simple, reliable, and repeatable. A method for isolating a definitive, objective means of comparing nano and macro-scale manufacturing processes is presented here to give design engineers a guide by which to create new nanomanufacturing technology.

This method uses two taxonomic ranks: High Level Metrics (HLMs) and Low Level Metrics (LLMs). High level metrics refer to abstract aspects of the process that are independent of things like the machine tool geometry, or the product that the process is used to manufacture. Low level metrics provide more detail about the inherent process characteristics (like it's cycle time) when that process is paired with a specific machine architecture (e.g. a C-type machine frame), or used in a specific place in a manufacturing system (for example a CMM at the end of a manufacturing line).

3.1.1 High-Level Metrics

Different types of manufacturing processes can be defined, as formulated in the material flow system aspect of Alting's model of manufacturing processes [66], by the following three characteristics:

1. Type of process
2. State of the workpiece material
3. Nature of the processing energy

These characteristics form the basis for the formulation of high-level metrics for both macro nanomanufacturing. This classification, or taxonomy, is a tool which can prove valuable in identifying and comparing the capabilities of nano- and macro-manufacturing processes.

The type of process refers to two major divisions which are distinguished based on whether or not the workpiece is shaped or its geometry modified during the process. *Shaping* processes change the workpiece shape or geometry, while n*onshaping* processes do not. Nonshaping processes can also be referred to as *treating* processes because they can be used to "treat" a material and modify its chemical or compositional characteristics. On the other hand, shaping processes can be divided into three distinct categories: mass-conserving, mass-reducing, and joining [66]. In macro-manufacturing, examples of shaping processes include milling, turning, and forging; examples of non-shaping processes include heat-treating, quenching, and doping.

The second characteristic, the state of the workpiece material, refers to the physical state of the material while it is undergoing the specific shaping or nonshaping process. Whether the workpiece material is in a solid, liquid, granular, or vapor state, each of the different types of processing energies can be used to modify the material in some manner. This gives rise to the third defining characteristic of manufacturing processes. It should be noted here that Alting's model only deals with shaping processes when describing the state of the workpiece and the third defining characteristic.

The nature of the processing energy is the third characteristic, and it generally takes one of the following three forms: mechanical, thermal, or chemical. While there are many different forms of energy, including electrical and irradiative, these three are the most prevalent among manufacturing processes. Processes which utilize electrical energy can be assumed to take advantage of the chemical potential energy contained within the workpiece material (such as Electro-Discharge Machining); while those processes which use irradiative energy to modify the workpiece material generally involve the use of heat transfer through irradiation: for example, heat treatment and subsequent annealing of steels. Table 3.1 shows the different process families which can be identified using the taxonomic breakdown described above [66].

Table 3.1: Taxonomic classification of different types of manufacturing processes as described by Todd [[66]].		
Type of Process (family)	State of Material	Nature of Process Energy
Shaping Processes		
1. Mass-reducing	Solid	Mechanical
2. Mass-reducing	Solid	Thermal
3. Mass-reducing	Solid	Chemical
4. Mass-conserving	Solid-granular	Mechanical
5. Consolidation	Liquid/plastic	Mechanical
6. Joining	Solid (except adjacent surfaces)	Mechanical
Nonshaping Processes		
7. Hardening	Solid	Chemical/thermal
8. Softening	Preparation	Mechanical/thermal/chemical
9. Surface treatment	Solid	Chemical/thermal
10. Surface treatment	Solid	Chemical/thermal

3.1.2 Low-level metrics

The low-level metrics used to characterize a (nano-)manufacturing process include the previously described variables most commonly used to generally describe manufacturing processes and systems: the rate, cost, quality, and flexibility. These are "low-level" metrics not because they are not as important as high-level metrics, but because these are process variables which refer to similarities among the extrinsic properties of a manufacturing process.

3.1.2.1 Rate

Rate, as described before, can have several different units and in conventional manufacturing can be taken as the cycle time of the slowest machine in the manufacturing system or the rate at which parts or finished components are produced from the system as a whole. In terms of metrics, it is probably best assumed that rate is taken as the total time required for the smallest individual workpiece unit to pass through the system. The smallest individual workpiece unit could be a single aluminum casting, a monolith-type fixture to which several parts are affixed, or a single gold substrate sample on which tens of thousands of nano-features are created.

3.1.2.2 Cost

Cost, the next metric considered in the low-level comparison of manufacturing metrics, can be taken in terms of the cost of an individual machine to enable the process, or as the cost per workpiece unit (the same workpiece unit above). It is essential that the low-level metrics be normalized to the same functional unit as their macro-scale counterparts so that a more accurate comparison of the metrics between manufacturing scales can be made, especially when considering cost. Every "0" after the decimal point increases cost dramatically; at the nano-scale this can mean the difference between finding a closely related metric and not finding any good matches.

3.1.2.3 Quality

When comparing low-level metrics for macro- and nano-scale manufacturing processes, the comparison must be scaled relative to the process. It would be better to evaluate processes on a qualitative quality scale rather than on their ability to achieve a desired tolerance. In macro-scale machining, quality is often referred to in terms of dimensional accuracy, as well as the dimensional constancy from part to part. These relative measures are also useful in identifying similar nanomanufacturing processes than would be simple direct comparisons of the dimensional capabilities of different processes as the drastic differences in scale would tend to skew any solid comparison.

3.1.2.4 Flexibility

In terms of comparisons between nano- and macro-manufacturing processes, the simplest definition of flexibility is the best to use. Flexibility measures the ability of a process is its ability to adapt to changes associated with all aspects of the surrounding manufacturing environment, including other manufacturing variables. It can also be used to describe how many different products are able to be manufactured by the process as well as its ability to achieve different standards of quality [12].

3.2 Nanomanufacturing Technology Synthesis

As stated at the beginning of Chapter 1, in order for nanomanufacturing to be enabled and implemented on a large scale, manufacturing technologies to enable those processes are absolutely necessary in order to take full advantage of the impact a process can have on society. Additionally, as before, in order for nanotechnological products to live up to their expectations, their manufacture must be of such a volume to meet demand, and be delivered in a "reliable, repeatable, economical and commercially viable manner" [2, 3, 5]. In short, in order for nanotechnology as a whole to affect its potential impact on society, there needs to be economically sound, reliable design, development, and implementation of nanomanufacturing technology.

In order to effectively design and develop new nanomanufacturing technology, a process is needed that is repeatable and reliable. Metric mapping between a nanomanufacturing process and a group of macro-manufacturing processes is one such method which has been demonstrated to be effective at identifying areas in existing nanomanufacturing technology which do not fulfill the process requirements of an individual nanomanufacturing process.

3.2.1 Metric-Mapping

The metric mapping (METMAP) process is carried out in cycles, much like a deterministic design process using FRDPARRC[4] [67] is utilized to "chip away" at a larger design problem by tackling small nuggets. METMAP uses 5 steps to isolate a macro-manufacturing process (from several candidate processes) which is the most similar to a single nanomanufacturing process. The 5 steps of METMAP are as follows:

1. Process identification
2. Comparison of high-level metrics
3. Process physics
4. Comparison of low-level metrics
5. Identification of "best" candidate macro process

The first step in metric mapping is to identify the nano-process that will be enabled by any resulting manufacturing technology, as well as several candidate macro-scale processes.

[4] Functional Requirements (FRs) + Design Parameters (DPs) + Analysis (A) + References (R) + Risks (R) + Countermeasures (C).

These macro-manufacturing processes are chosen at an individual's discretion, and the process as a whole may take multiple iterations with different candidate process groups to yield results. After the processes have been identified, the next step in the process is used to identify general similarities between nano and macro- processes.

The second step, the comparison of HLMs, compares the three characteristics of a single nanomanufacturing process with each candidate macro-manufacturing process in order to identify similarities between high-level metrics of each process pair. When a group of between 4 and 10 macro-manufacturing processes are identified by their HLMs to be similar to the nanomanufacturing process, the physics of each process are then described and evaluated to ensure a solid understanding of each. A good understanding of the physics that drives a process is essential in order to accurately compare it to other manufacturing processes.

After an understanding of each process is achieved, the next and perhaps most critical step is reached: comparison of LLMs. This is where the final candidate processes are identified before physical machinery and enabling technology is evaluated. Once a macro-process is identified as being similar to the nano-process on this level, a design engineer can begin to get an idea of the type of technology which could be used to enable the desired nanomanufacturing process. The overall metric mapping process can be illustrated as a flowchart, as seen in Figure 3.1. In Chapter 4, a precision machine to enable Dip-Pen Nanolithography is used as a case-study to demonstrate the effectiveness of the metric-mapping process.

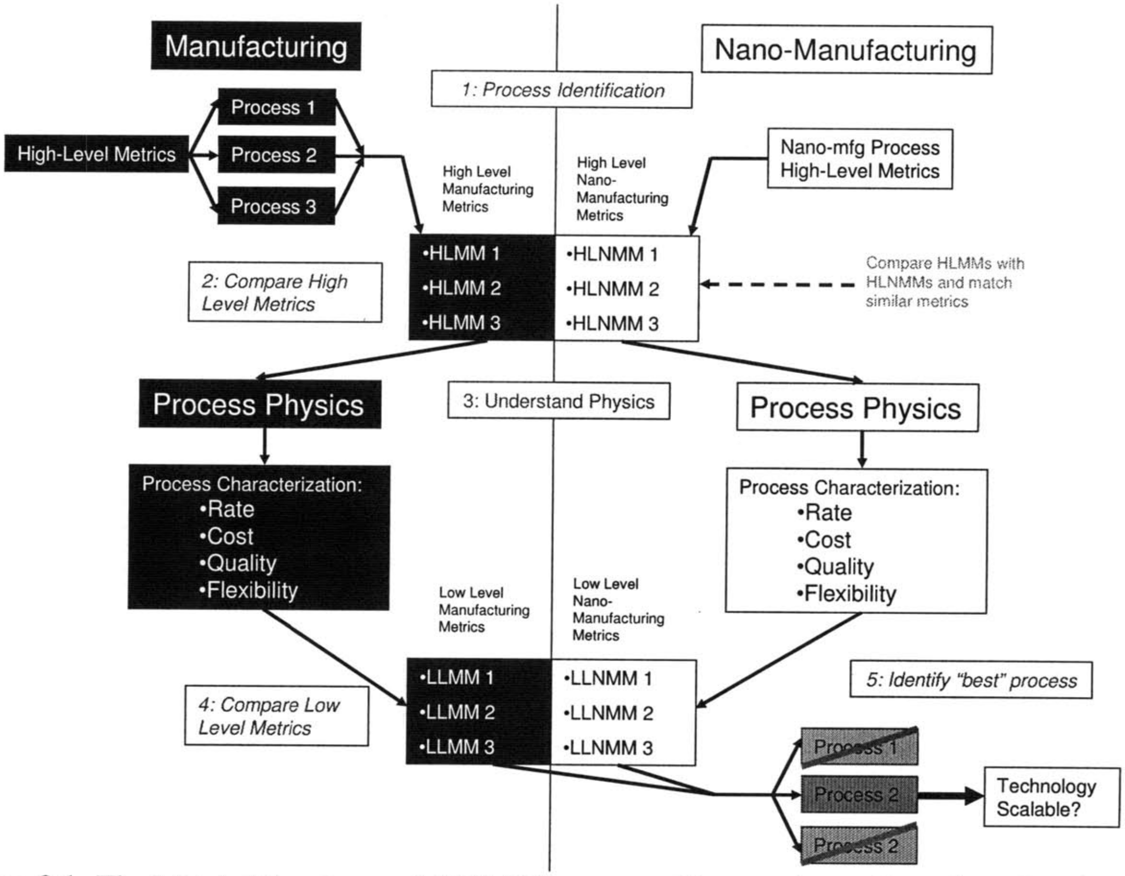

Figure 3.1: The Metric Mapping, or METMAP, process illustrated as a flow chart showing: 1) Identification of candidate processes, 2) Comparison of HLMs, 3) Understanding the physics of the process, 4) Comparison of LLMs, and 5) Identification of the "best [macro-] process" to enable a nanomanufacturing process.

CHAPTER

4

CASE STUDY: DESIGN OF A NANOMANUFACTURING MACHINE

4.1 Design Process

The design of a nanomanufacturing machine was carried out with the goal of designing a machine which would be capable of enabling a scanning-based process such as Dip Pen Nanolithography (DPN), at a rate which would make it an economically feasible process. An experiment conducted at Ohio State University's NSEC, which required a pre-determined amount of DNA to be processed using DPN, was examined as an area in which improvement in nanomanufacturing technology could have significant impact. This rate analysis was a significant driving force in optimizing the machine geometry and helping to choose the layout which provided the lowest processing time to the least cost (whether it be energy, time, materials and waste, etc.).

Furthermore, inherent to both scanning-based processes which have been made massively parallel (by the use of an array tool) and template-based processes, is the need for planar alignment between the tool (one plane) and the workpiece/substrate (another plane), as can be seen in Figure 4.1.

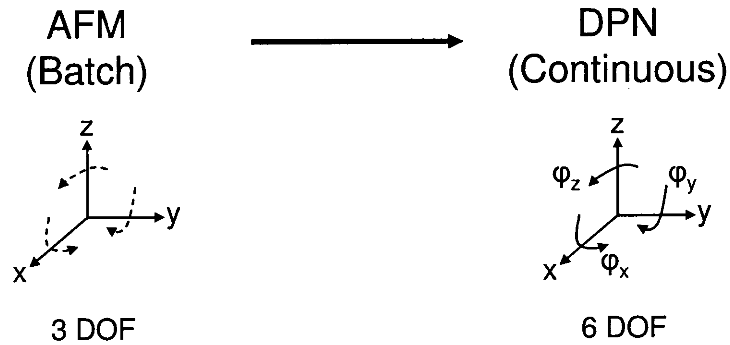

Figure 4.1: Single-axis alignment (left) and 6-axis alignment (right) critical dimensions. For an AFM tip (single-axis), the Z dimension, or tool offset, is the critical process dimension. For template-based and massively-parallel nano-scale processes, planar alignment (right) means that tool offset (Z) and tip/tilt (X, Y rotation) are critical process dimensions.

From this an opportunity presents itself to take advantage of benefits of kinematic couplings to align two surfaces with high accuracy and repeatability. This benefit is amplified by the use of flexure-modified kinematic couplings [68] which further increase the repeatability that the system can obtain, down to about 30 nm, or of the order required for enabling the manufacture of nano-scale products.

Designing for high-rate DPN meant developing a new machine for enabling a scanning-based nanomanufacturing process. Several existing architectural layouts for macro-machining were evaluated and resulted in the synthesis of the metric-mapping process. Additionally, discussions on the best practices associated with designing nanomanufacturing machines, studies of the progression of macro-manufacturing processes, and a class on Manufacturing Processes and Systems (MIT Course 2.810, Fall 2008) contributed to the thought-process which resulted in the metric-mapping method.

For this nanomanufacturing machine, the design process was executed without any concrete guide-lines or design methodologies for designing nanomanufacturing equipment. The metric mapping method was the result of a perceived need in stream-lining this process, and to help other design engineers create their own machines for nanomanufacturing by either using the metric mapping method or thereby confirming that their own methods are sound. Performing a self-assessment on the flow of ideas/thoughts/concepts through the design notebooks used in this project were the motivation for the metric mapping method.

The first step in the design process (using the results from the DNA rate calculation) was to determine the machine architecture which would best support the "palletized" format specified by the 2-D substrate array utilized in massively-parallel DPN. Analogous machining processes which operate with "palletized" product units include those such as thermo-forming, processes which utilize pick-and-place robots, stamping, and forging. These were the basis for the "candidate processes" in the metric mapping method and the comparison resulting from this step utilizes high-level metrics.

The second step in the design process was to understand the physics of both types of processes (nano- and macro-scale). Power estimates for utilizing each type of machine architecture for nano-scale fabrication identified the most efficient machine layout. The low-level metrics of rate, cost, quality, and flexibility were then used to modify the chosen architecture so as to satisfy both the functional and customer requirements, as well as the need for high-throughput manufacture of nano-scale products.

Finally, the functional requirements, chosen machine architecture, and an understanding of the process physics were used in conjunction with a deterministic process to develop a first-order proof-of concept design. A sketch-model of the resulting design was constructed. This allowed for better visualization of the chosen machine architecture and a platform from which to make improvements to the chosen concept. Through continued applications of a deterministic process the design underwent several iterations until a design was achieved which was the most representative of generally accepted best practices in design and manufacturing.

This machine was then fabricated and its capabilities assessed to show that it was, in fact, capable of meeting the necessary performance in terms of its components' accuracy, precision, repeatability, and throughput. After this was completed, the design was further improved to make it modular, so that it could be used to enable multiple nanomanufacturing processes. The final nanomanufacturing machine is capable of high-throughput, ultra-high precision positioning of a sample/substrate/workpiece relative to the tool at a rate consistent with that required to enable high-throughput nanomanufacturing, and more than 2 orders of magnitude greater than what is currently available (10 seconds vs. 30 minutes).

4.1.1 Metric Mapping

The metric mapping method is demonstrated here to show how it can be used to influence and aid the design of a nanomanufacturing machine for Dip Pen Nanolithography. The 5 steps of the METMAP process used in this case study, as detailed in Chapter 3, are as follows:

1. Process identification
2. Comparison of high-level metrics
3. Process physics
4. Comparison of low-level metrics
5. Identification of "best" candidate macro process

4.1.1.1 Process Identification

The nanomanufacturing process for which this machine is being designed is Dip Pen Nanolithography. DPN is a scanning-based lithography process that uses an AFM tip to write on a substrate containing any number of target particles for "inking". Candidate macro-manufacturing processes include thermo-forming, injection molding, forging, milling, turning, and welding. These are outlined in Table 4.1.

Table 4.1: Identification of macro- and nanomanufacturing process for METMAP.

Candidate Macro Processes	*Nanomanufacturing Process*
Sheet Forming	Dip Pen Nanolithography
Injection Molding	
Forging	
Milling	
Turning	
Welding	

Each of these candidate processes is well-understood, and models for the respective process physics exist which allow engineers to optimize these manufacturing processes for a given application. For example, thermal models are used to improve the performance of, and the quality of parts created by, molds for injection molding; modeling the mechanics behind finite-deformation plasticity can be used to predict the flow of dislocations in a forged component, and to identify optimal heat-treatment procedures for the forging to increase material properties such as yield stress or elastic modulus. Dip Pen Nanolithography, however, is in its infancy, and detailed process models are still being developed [69].

4.1.1.2 Comparison of High-Level Metrics

The next step in the metric mapping process calls for a comparison of high-level metrics between each candidate process and the target nanomanufacturing process. High-level metrics which should be assessed include:

4. The type of process (shaping vs. nonshaping)
5. State of the workpiece material (solid, liquid, granular, etc.)
6. Nature of the processing energy (mechanical, thermal, chemical, etc.)

With the first HLM we see an opportunity for improvement upon the METMAP method: is DPN a shaping or non-shaping process? At the scale of the sample, it is a coating or inking (writing) process, but on the atomic scale, the ink could induce a conformation change in a target molecule, thus making DPN a hybrid shaping/non-shaping process.

The second HLM must be considered to address this apparent confusion: The workpiece material is a solid (usually a gold substrate in the case of DPN), thus eliminating injection molding as a candidate macro-manufacturing process. Additionally, the delivery of energy to the workpiece can occur either physically or chemically, eliminating welding as a candidate process (chemical and vibration welding would be covered under chemical and mechanical delivery of energy). Thus, the candidate processes which remain are sheet forming, forging, milling, and turning.

4.1.1.3 Process Physics

A physical model of the DPN process has not yet been perfected, published, and independently verified. Here it becomes apparent that the METMAP method is not perfect; it breaks down for those nanomanufacturing processes which are not very well understood. Research on the physics of DPN is ongoing [69]. For situations such as these, the process can be treated as a black box and the low-level metrics used to match a nanomanufacturing process with best candidate processes.

4.1.1.4 Comparison of Low-Level Metrics

The low-level metrics used here are the rate, cost, quality, and flexibility of the various nano- and macro-scale processes. For a DPN machine, rate is the critical variable because the primary goal is to increase through-put. Sheet-forming, milling, turning, and forging processing times all depend on the complexity of the part being processed manufactured. In DPN, the "part" is generally a flat plate, which indicates that sheet forming and milling would be the most similar processes for which processing of flat plates would be rapid; thus turning and forging were eliminated as target processes.

Which process between sheet forming and milling is better? A design engineer entering this step of the METMAP process without *a priori* knowledge of the final machine architecture would be required to utilize a deterministic process to isolate a specific design: utilizing functional requirements from both sheet-forming and milling machines, concept generation would utilize technologies present in high-throughput applications of both of these macro-scale processes. Application of the deterministic process and relation of functional requirements to the perceived performance of a given machine architecture is key to this step of the process yielding a robust design.

If one were to examine the current nanomanufacturing machine presented as the main body of work for this thesis, it would be apparent that technologies currently used in both macro-processes (belt-driven indexing, and fixturing of a flat workpiece relative to a tool) are utilized; they have been scaled down and modified to enable high-throughput Dip Pen Nanolithography. It should also be noted that the METMAP process is not set in stone. While it is a generalized process for designing precision machines for nanomanufacturing, it can be modified to suit the application and assumptions can be made and later verified or proved inaccurate. Improvements to the method can be implemented when a successful design is generated and shown to work.

Additionally, METMAP is not a guarantee that a "best" design will be achieved. This requires a design engineer to possess some skill at designing machines to begin with, as well as knowledge of various manufacturing systems (Chapter 1) and nanomanufacturing processes (Chapter 2).

4.1.2 Rate Analysis Case Study: DPN Linking of DNA

The rate analysis performed on an experiment driven by Dip Pen Nano-lithography processing of DNA molecules can be seen in Figure 4.2. From this result it can be seen that using a cycle time on the order of 10 seconds (0.1 Hz), processing enough DNA to run 1 experiment (1 μg) would take 400 days (the current DPN machine has a cycle time of 30 minutes). Simply increasing the cycle time is not feasible, as the DPN writing process itself can operate over a range of just a few to several seconds.

Req'd Mass of DNA	0.000100	g
Tip Number	55000	tips
Number of Trays	1	
Number of Arrays	1	samples
Array Speed	0.1	Hz
Yield	100	%
Required time	402.4	days
Required time	1.10258	years
Production rate	2.48E-07	g/day

Figure 4.2: DPN Rate Calculation

As such, with the cycle time at a minimum of 10 seconds, the other areas in which improvements can be made are the number of tips in an array of tools, or the number of machines. Purchasing 30 DPN machines at a cost of several hundred thousand dollars per machine is no economically feasible for any but the largest of companies. Additionally, large numbers of highly-trained personnel will be required to operate and maintain a fleet of such machines. A low-cost, efficient, easy-to-operate and maintain nanomanufacturing machine would fulfill this need; parallelization on a machine-level is necessary given the limit imposed on the cycle time. If 30 such machines (each with a cycle time of 10 seconds) were to be operated in parallel, the production time would be reduced to 10 hours, or around 0.4 days, as seen in Figure 4.3. In order for this to be feasible the total cost must be equal to or less than that of the current machine; each machine should cost on the order of a few tens of thousands of dollars (the current technology is on the order of hundreds of thousands of dollars).

Req'd Mass of DNA	0.000100	g
Tip Number	55000	tips
Number of Trays	1	
Number of Arrays	30	samples
Array Speed	0.1	Hz
Yield	100	%
Required time	0.4	days
Req'd time (hrs)	10.7	hours
Req'd time (yrs)	1.23E-03	years
Production rate	2.24E-04	g/day

Figure 4.3: Modified DPN Rate Calculation to show 30 parallel machines.

A machine that increases the overall rate at which nano-scale features could be produced would greatly improve the production capabilities of nanomanufacturing technology. A machine that increases the rate *and* is significantly more cost-effective than current technology would have potential for significant impact on the fledgling nanomanufacturing technology industry.

4.1.3 Analysis of Acceptable Machine Architecture

The initial goal of this project was to design a desk-top machine for enabling high-rate nanomanufacturing. As part of the deterministic design process, several machine concepts were created (Figure 4.4) and their relative "good-ness" was assessed using a PUGH chart (Figure 4.5). The parameters in the PUGH chart were rough functional requirements, as the detailed functional requirements had not been formulated as-of-yet.

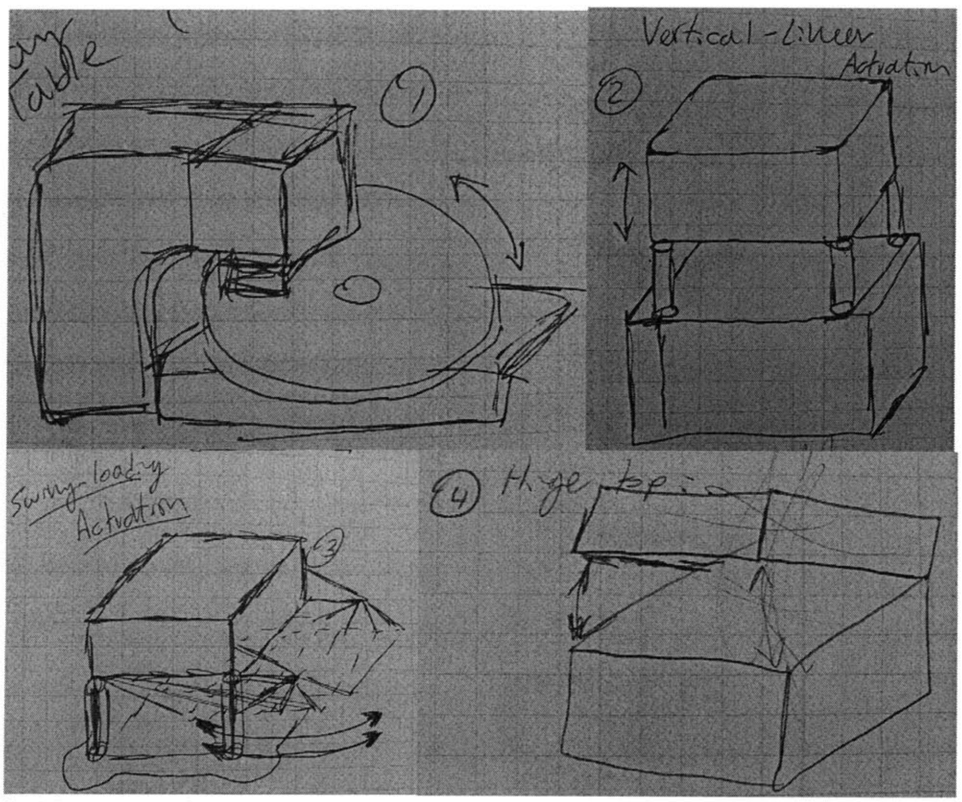

Figure 4.4: Nanomanufacturing machine concept sketches including: rotary tables, swing-loading machines, vertical-motion stamping machines, and hinged-gantry machines.

Concepts	Support ~X Sample Trays Compactly	Load / pre-load / unload samples	Thermally Stable	Vibrationally Stable	Indexing System Power	Nano-positioning System Power Efficiency	Material Handling System Power Efficiency	Sensing System Power Efficiency
Rotary C-frame	0	0	0	0	0	0	0	0
Linear linkage/lever assembly (x-y)	-1	-1	0	0	-1	-1	1	0
Lift-up top head design (z)	-1	0	0	0	-1	-1	1	0
Hinged head (like objet)	0	-1	0	0	-1	-1	1	0
Rotary H-frame	0	0	1	1	1	0	0	1
Linear H-frame	-1	0	1	1	-1	-1	1	1

Figure 4.5: PUGH chart for various machine architectures and production layouts. It should be noted that the second-generation nanomanufacturing machine is a version of the "linear H-

frame" design depicted here, which was not selected initially.

One possibility which was discussed during a design review was to incorporate a rotary table into the design of the nanomanufacturing machine, as evidenced by the "Rotary C/H-frames" examined in Figure 4.5. These are often seen in thermo-forming applications, and are widely utilized because they are easily manufactured, simple to model, and very effective at efficiently transporting materials to and from the workpiece. It should be noted that while during the metric mapping case study thermo-forming was elminated as a candidate process, a deterministic process was used, which lead to the creation of the metric mapping method, to eliminate thermoforming through analysis of the process physics. The basis for the utilized "sample tray" was a piece of previous work that placed 10 Hex-Flex nanopositioners in a staggered array on a single "tray". This layout can be seen in Figure 4.6.

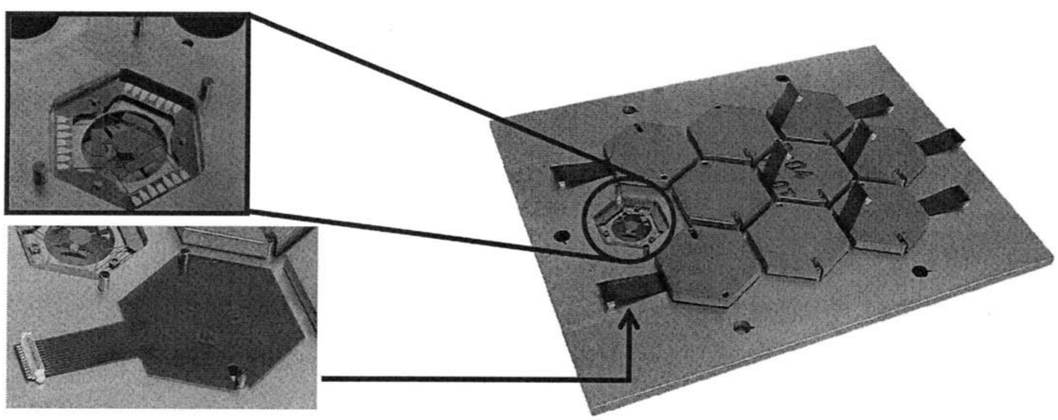

Figure 4.6: Hex-Flex sample tray.

The Hex-Flex "tray" would be part of the tool. Each tray would mesh with a corresponding "sample tray", and each Hex-Flex would operate on a separate workpiece. However, in order to increase throughput, multiple Hex-Flex trays could be added, which could also lead to increased flexibility as each Hex-Flex tray could perform a different operation, then when the tray is incremented once, the next Hex-Flex tray could perform another operation. Furthermore, given that a sample tray is 250mm x 375mm, putting more than 2 or 3 on a rotary table machine would make it much larger than an acceptable "desktop" machine.

As such, the diameter of a rotary table with respect to the number of "sample trays" it would support was estimated. There are two viable configurations for the sample trays as well. Each sample has a long dimension and a short dimension, and arranging the trays with each of these dimensions orthogonal to the outward radial vector of the rotary table would result in different table diameters for the same number of trays (except in the case where there are 7 sample trays, as can be seen below in the figure). Figure 4.7 shows a plot of rotary table diameter versus the number of trays on each table, as well as solid models of a few representative "long-type" trays (with the sample tray's long dimension oriented orthogonal to the tables radial vector).

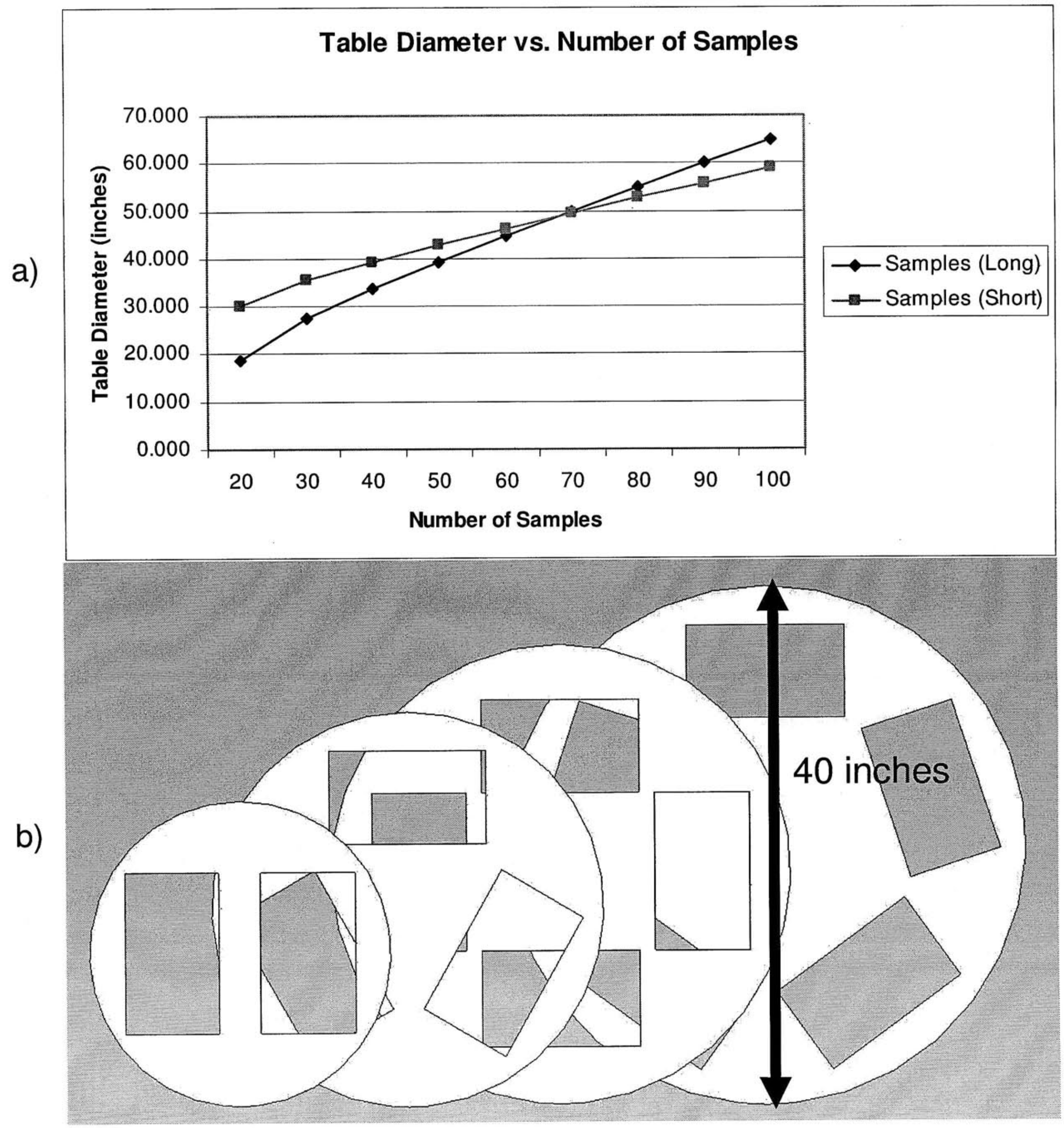

Figure 4.7: (a)Rotary table sizes; (b) a solid model of four "long-type" trays with characteristic dimension of the tray diameter.

From Figure 4.7 it can be seen that the previous estimate of a desktop machine being limited to between two and three sample trays was accurate: a rotary table with 4 sample trays would required a minimum table diameter of about three feet, which when integrated with the supporting machine architecture and other components would be too large for a desktop environment. This then begs the question that if a rotary table architecture is not suitable for efficient, economical high-rate nanomanufacturing in a desktop-scale environment, what would the machine look like if it were not restricted to a desktop? The machine presented here ends up fulfilling both scale requirements. A single module or two can be placed on the desktop, while a large manufacturing line could be implemented as well.

The production rate, in terms of grams of DNA produced per day of operation, of rotary tables was plotted with respect to the number of sample trays on the rotary table. Additionally, the cycle time was examined as another variable that could be modified to influence the total time required to produce enough DNA to run the representative experiment (the rate analysis from Section 4.1.2). Figure 4.8 shows the plot of DPN daily production rate vs. number of trays. The cycle time of 10 seconds was initially examined in the rate analysis, and the 5 and 6 second cycle time graphs are included for reference.

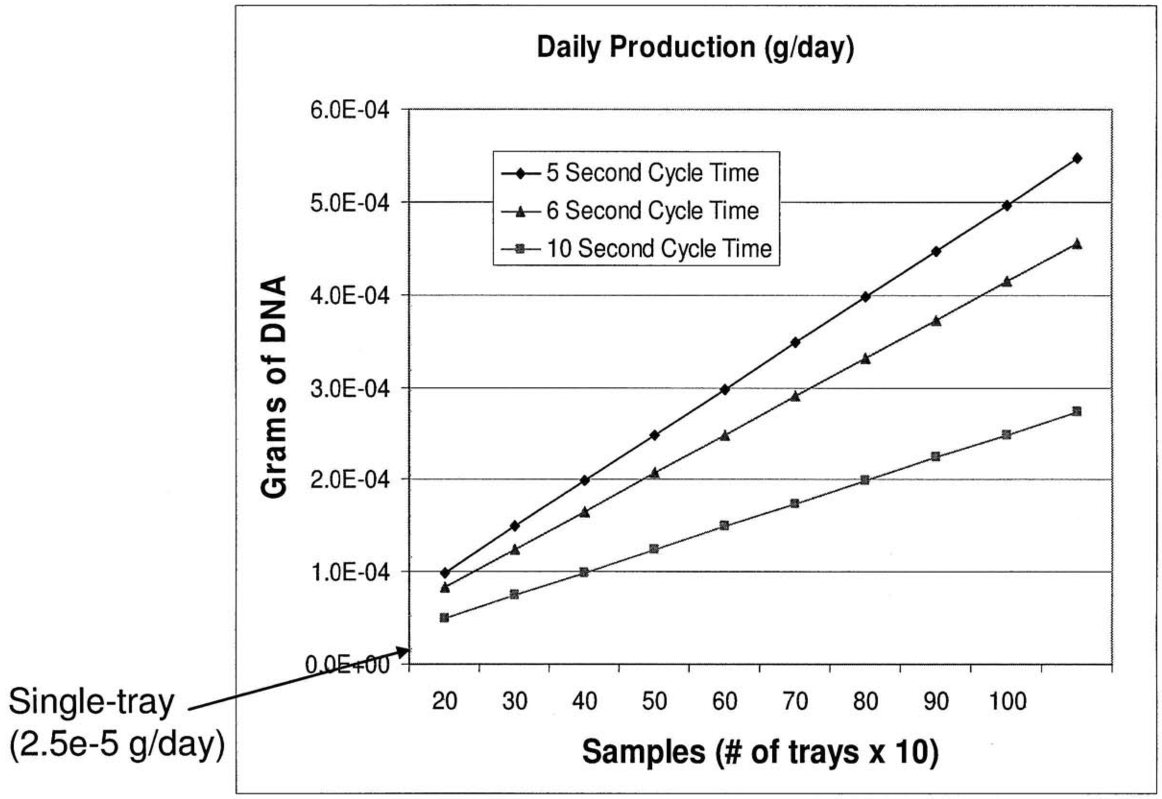

Figure 4.8: DPN daily production rate vs. number of trays; cycle times of 5, 6, and 10 seconds are shown.

As was expected, the daily production rate simply scales linearly with the cycle time and the number of trays. A rotary table with 6 sample trays (60 samples), operating with a 10 second cycle time has the same production rate as a 3 sample tray table (30 samples) operating with a 5 second cycle time. This analysis was necessary to identify similar configurations of cycle time, rotary table size, and number of samples for reasons of optimizing the power consumption profile of the machine. It was then concluded that the power required to drive a rotary table scales with the square of the cycle time.

A 10-second cycle time would require about the same amount of power as a 5-second cycle time. The increased mass of the machine (which would use more sample trays to equal the production rate of the higher-speed machine) accounts for the difference created by the reduced time of the 5-second machine. Additionally, the machine might eventually be required to operate at different cycle times for different processes, which would have added an entirely new dimension to the design process. Fortunately, during a design review a concept for a belt-driven nanomanufacturing machine was conceived, thus leading the project in a different direction.

4.2 Design of a Nanomanufacturing Machine

The first concept utilizing a belt-drive was a sketch that was conceived during a design review can be seen in Figure. The concept was later modified slightly during a design review. The first belt-drive concept sketch can be seen below in Figure 4.9. The paper on which the concept was sketched had been pasted into the design notebook for this project, and was used as the basis for the solid model of the machine seen in Figure 4.10. This solid model forms the basis for the general machine architecture of this nanomanufacturing machine.

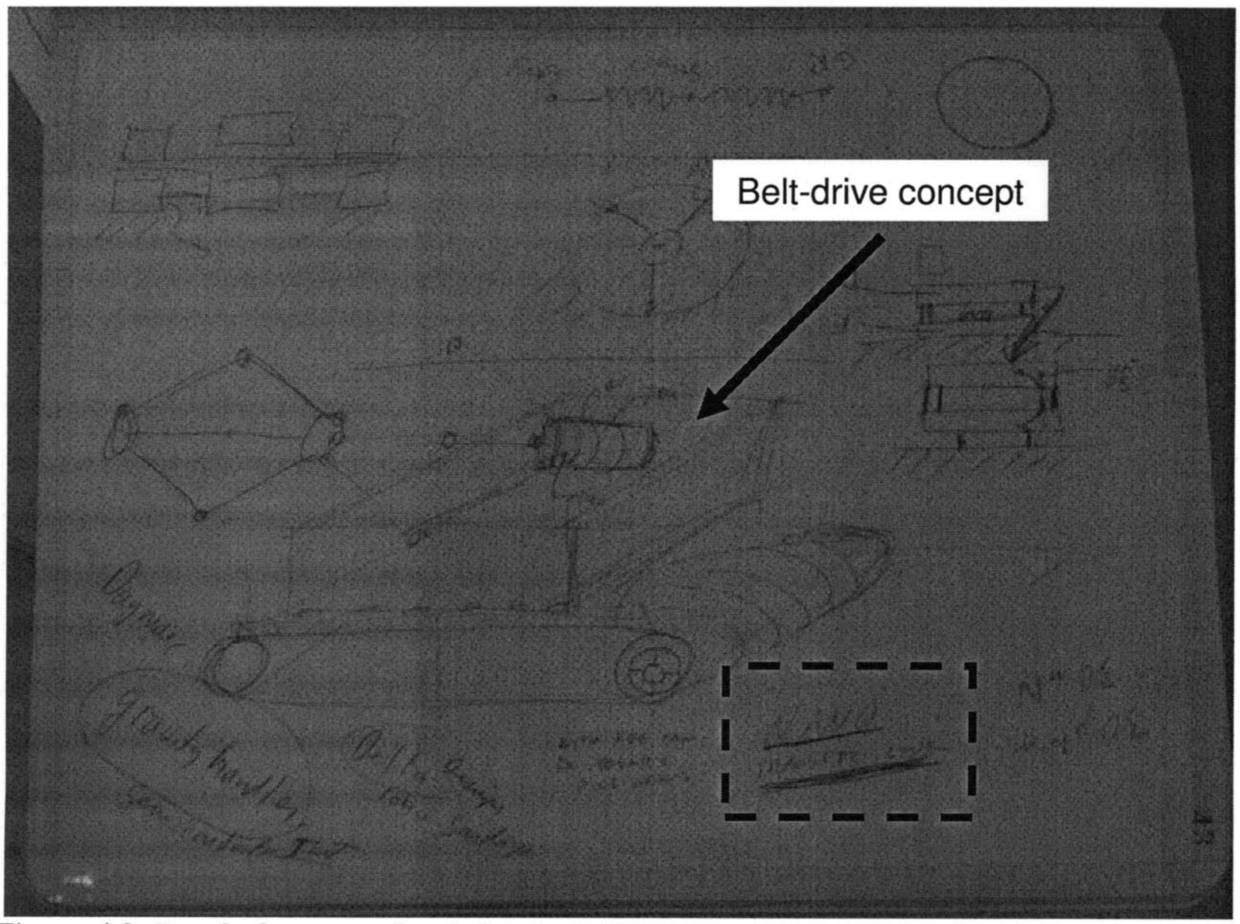

Figure 4.9: Proof-of-concept sketch for the belt-drive model, pasted in a design notebook. The dashed line shows the first mention of the term "nano-transfer line" during this project.

The goal of this sketch-solid-model was to provide a more accurate illustration of the 3-D concept of using a belt to transport small samples to a write head or tool. Additionally, it was first postulated that the rollers used to support and drive the belt (via the capstain effect) should be manufactured to include some sort of thermally-compensating structure, as well as structures for minimizing the transmission of vibration to the sample. This was later determined to be an inaccurate assumption; the belt drive was in and of itself relatively imprecise, and once the sample was pre-loaded to its fixture then all other structures in the machine could essentially be ignored.

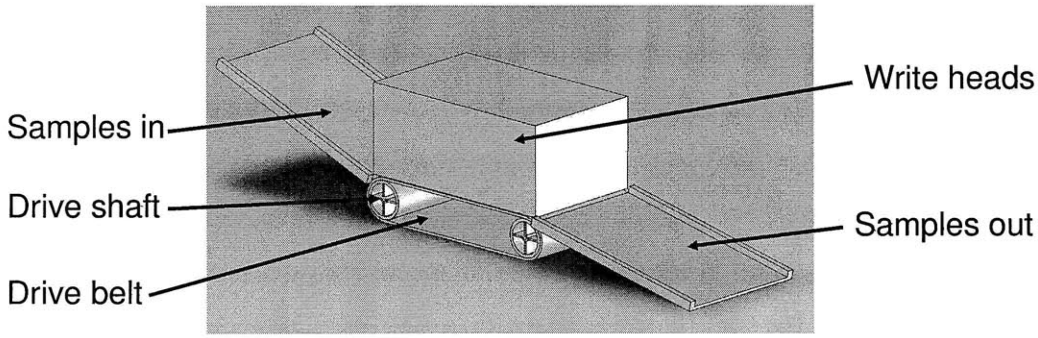

Figure 4.10: Solid model of the proof-of-concept sketch for the belt-drive nanomanufacturing machine.

Using the results of the METMAP process, the hybrid belt-drive/transfer line technology was described as the "best" machine architecture for enabling DPN. Thus, a proof-of-concept machine was fabricated to illustrate the scale and behavior of a belt-driven machine. This sketch model, shown in Figure 4.12, was made utilizing a 3-D printing process to fabricate a majority of the structures. The belt was tensioned using constant-force springs, and plastic pillow-block bearings acted as supports for the belt rollers. A power budget for the spring-loaded belt-drive sketch model was also created to determine the required force for an actuator to drive the belt. From this a Haydon-Kerk 4400 series hybrid linear actuator was sourced to drive the prototype machine, and can be seen in the figure below.

Power to move samples			
Description	Value	Units	Symbol
Mass of single sample block	**0.2**	kg/block	sb_mass
Number of sample blocks	**10**	blocks	sb_num
Mass to move	**2**	kg	mb
Distance to write head	**0.125**	m	d_wh
Time to move	**5**	seconds	t_m
Required Acceleration	0.01	m/s^2	
Required Force	5.19	N	
Required belt tension			
Constant-force spring load	**1.16**	lbs.	cfs_l
load (Newtons)	5.17	N	
Required Work	0.65	J	
Sample velocity	0.05	m/s	
Sample Kinetic Energy (check)	0.003		
Power to move samples	**0.13**	Watts	
Power to rotate driveshafts			
Radius of free roller	**0.05**	m	fr_r
Length of free roller	**0.25**	m	fr_l
Mass of free roller	3.53	kg	
Free roller roational inertia	0.004	kg-m^2	
Free roller rotational velocity	1	rad/s	
Rotational acceleration	0.2	rad/s^2	
Torque to accelerate roller	0.0009	N-m	
Power to accelerate roller	0.0000	Watts	
Worst case (2 solid shafts)	0.0001	Watts	
Total req'd Power	0.130	Watts	
	130	mW	

Figure 4.11: Power budget for the proof-of-concept belt-drive machine.

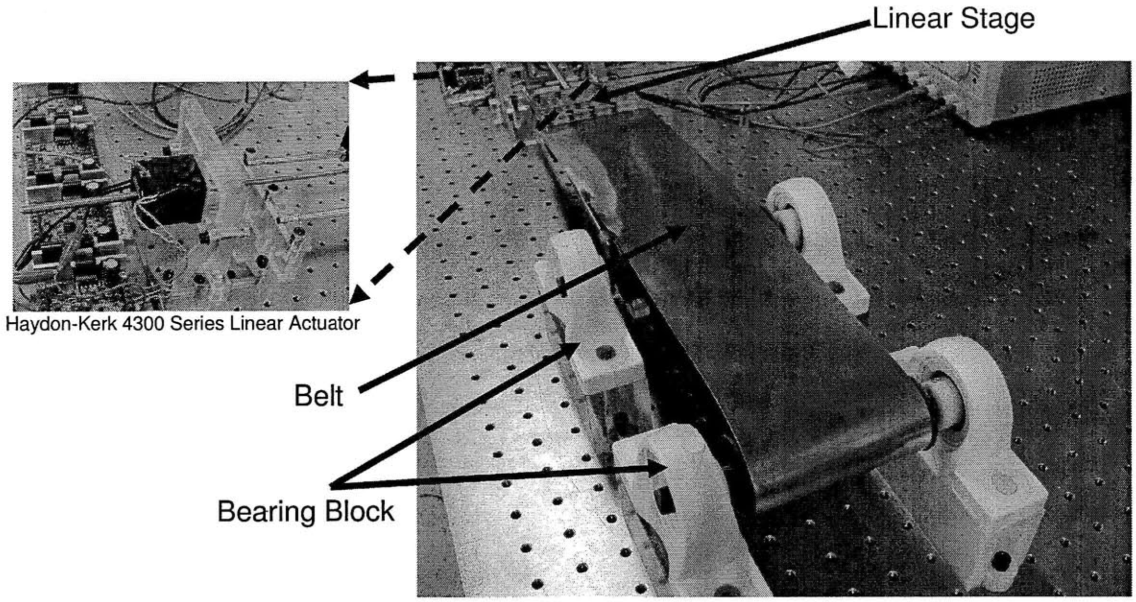

Figure 4.12: Proof-of-concept belt-drive machine. This sketch model was useful for highlighting some of the challenges associated with belt-drives, most importantly achieving proper tension in the belt, positioning accuracy, and also identifying the key features which would be considered in the error-budgeting for this machine.

This model highlighted the importance of maintained adequate belt tension, as well as the need for rollers to be crowned to maintain belt alignment. Furthermore, it should be noted that this model uses a belt which is non-continuous; the final nanomanufacturing machine utilizes a continuous belt with 4 rollers, one of them being drive by a motor and actuating the belt via a capstain drive. A manufacturer of precision indexing belts [71] and belt drives was eventually contracted to manufacture the continuous belt.

Additionally, using the belt drive leads to two discrete steps which must be carried out in order to transport the workpiece to the tool. The first is the coarse motion required to position the workpiece accurately below the fixture (within the capture distance of the kinematic coupling), and the second is the pre-load action which fixtures and aligns the workpiece relative to the tool. The belt manufacturer advised that the precision of a few hundred microns (the capture distance of the coupling) was more than easily achieved through the use of a properly tensioned belt using a capstain drive mechanism.

4.2.1 Error Budget

Early on in the design process it was postulated that using two kinematic couplings facing in opposite directions would allow for high-accuracy positioning/fixturing of a sample. As such, it was easy to estimate the approximate characteristic dimension with which errors in the system could be estimated: the distance between on feature of each of opposing flexure-modified kinematic couplings. This distance was on the order of 1.3 cm. An isometric section view of the opposing kinematic couplings for the tool and workpiece fixturing can be seen in Figure 4.13.

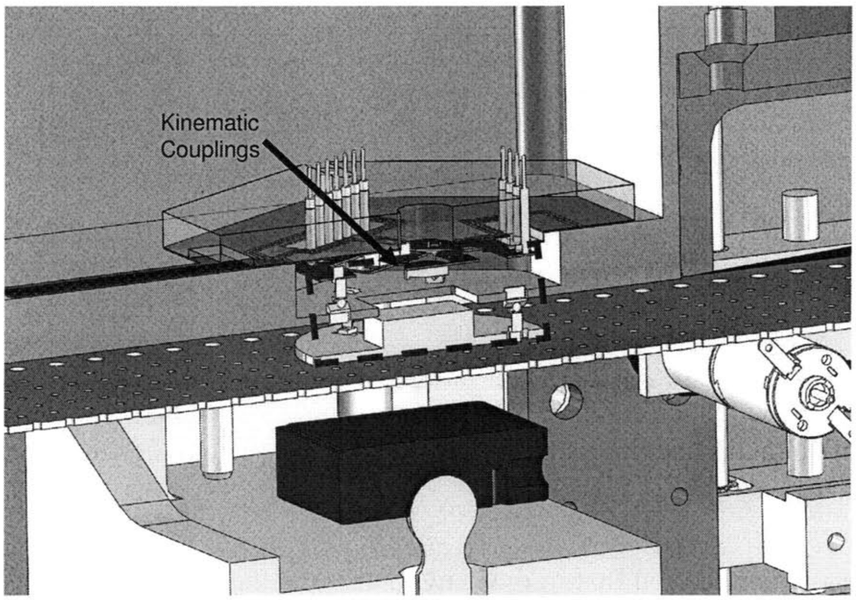

Figure 4.13: Isometric cut-away view of the sample and tool fixtures showing opposing kinematic couplings.

Using this assumption, the error budget for this machine was very simple. In order to minimize the error associated with the machines performance, the structural loop has been minimized so as to mitigate the effects of thermal errors, thermal drift, and mis-alignment of the tool with the substrate. Thus, the goal of minimizing the structural loop was achieve through the use of the opposing kinematic couplings.

Parameter	Value	Units	symbol
Web Char. length	0.02	meters	w_l
TEC Aluminum (6061)	1.30E-05	µm/m-℃	a_alu
Line Width	6.00E-08	m	del_T
Web expansion (10% line width)	6.00E-09	m	web_exp
Max. Temp. Change	0.02	℃	mtc

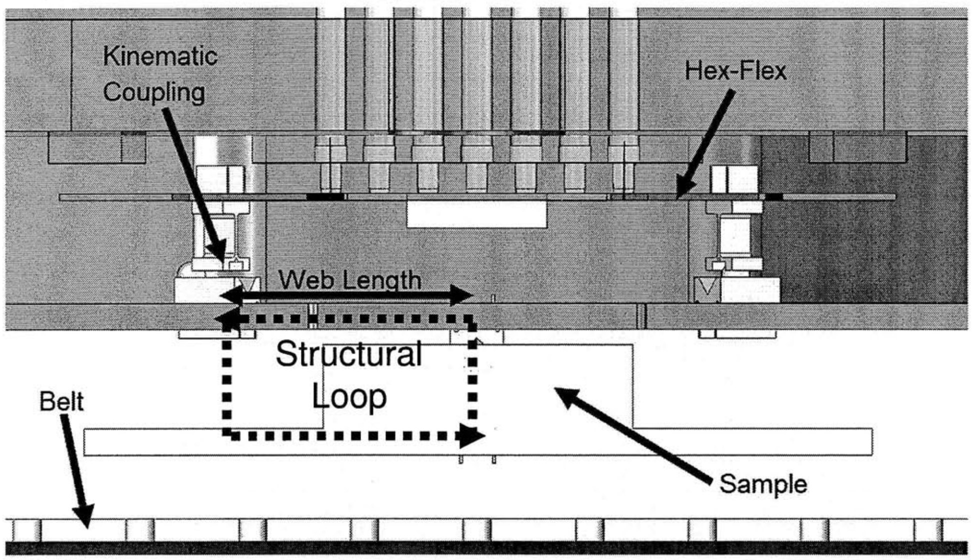

Figure 4.14: Error budget calculation for the nanomanufacturing machine (top). The structural loop is shown in a dashed line in this close-up cross-section of the kinematic coupling interface (bottom).

From this it can be seen that in order to control the thermal drift in the structural loop to no larger than 10% of the line-width of the nano-process, the temperature within the structure must be controlled to within +/- 0.01℃. Additionally, the work-piece/tool relationship is determined entirely based on the relative orientation of the kinematic couplings used to fixture each component, meaning that the surrounding supporting structure can also be ignored for purposes of error budgeting in tool/workpiece interaction.

Furthermore, outside of the accuracy and precision of the couplings, the required accuracy of the belt is on the order of several hundred microns (the capture distance of the coupling), which is easily achieved using a capstain-drive belt and an encoder-feedback driven DC motor. These were added to the second generation nanomanufacturing machine, after the purpose of the linear motor used in the concept sketch-model was changed to actuate the material handling structure (to pre-load the workpiece to it's fixture).

4.2.2 Machine Functional Requirements

The functional requirements for the nanomanufacturing machine can be seen in Table 4.2. These are based off of the specifications of the desired cycle time calculated in Section 4.1.2, as well as the required processing parameters for DPN and the machine error budget. These functional requirements are also relatively generalized for nanomanufacturing processes.

Table 4.2: Nanomanufacturing machine functional requirements.

Functional Requirement	Description
1. High positioning accuracy	6 microns - this is half of the travel distance of the Hex-Flex six-axis nanopositioner
2. High angular accuracy	800 μrad - planarity requirements for DPN process (8 microns over 1 cm).
3. Low docking time	Docking time just over the settling time for the kinematic coupling (~5 sec.); cycle time on the order of 10 seconds.
4. Cost	≤ $100,000.00. The current state-of-the-art is several hundred thousand dollars.
5. Thermally stable	Structural loop requires mitigation of thermal fluctuation to less than 0.06 °/min.
6. Automated	Able to run for long periods of time without human intervention (e.g. 2 weeks).

Most scanning-probe-based nanomanufacturing processes are implemented in a massively-parallel configuration through the use of arrays of probes, while template-based processes already utilize templates to begin with. As such, the planarity, docking time, and positioning accuracy FRs would be somewhat constant when designing for different processes.

It should also be noted that these functional requirements are *not* specific to a belt-drive machine, but can also be applied to the rotary table machine architecture previously mentioned. It is because of these generalized functional requirements that the design of the nanomanufacturing machine presented here is modular, able to be customized and arranged in series and parallel operations to fulfill a wide variety of different nanomanufacturing roles.

4.3 Modelling, Fabrication, and Testing

Once the belt-drive concept had been chosen as the material transport mechanism, the surrounding machine architecture needed to be designed. Both H-frame and C-frame type machines were considered; as with many of the ideas key to the success of this project, the design chosen was suggested during a design review after several concept generation cycles. The desire for a thermally-stable machine led to the suggestion of using a thermo-centric tube to take advantage of the symmetry of such a structure.

In Figure 4.15, schematics of C and H-frame architectures are shown deforming under non-uniform heating (heating of the just the outside surfaces of the machine) conditions from effects such as sunlight or radiation from heat sources commonly found in manufacturing environments (a large generator, for example). These errors are exaggerated purely to highlight the mode of deformation.

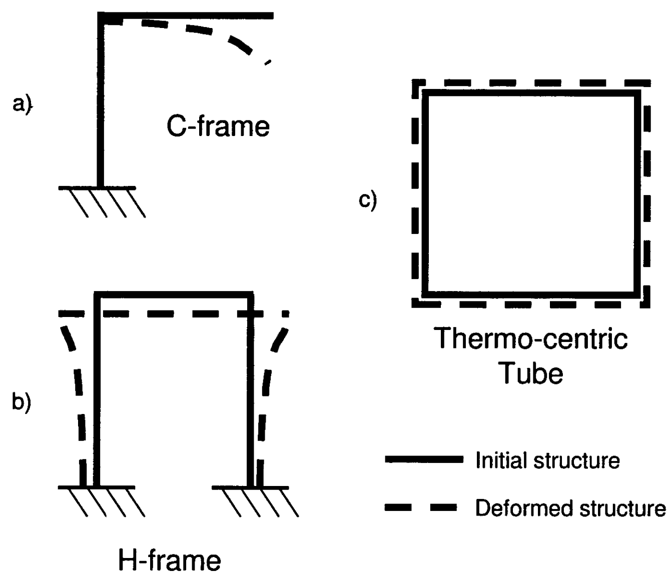

Figure 4.15: The use of a thermo-centric design (c) allows the nanomanufacturing machine to mitigate the effects of thermal errors which commonly effect other machine architectures.

Once the machine architecture was chosen and designed, the supporting structure or "guts" of the machine which would allow it to enable a nanomanufacturing process were designed. For the first-generation machine these were designed with ease-of-manufacture, cost, ease-of-assembly, and testing as the most critical parameters to optimize. The goal of this machine was to prove that the thermo-centric tube could be used to support a belt-drive capable of transporting a sample to the tool, pre-loading and fixturing it with high-precision, and then transporting the sample away from the tool.

One additional benefit of the belt-drive that has become apparent is the combination of two of the material transport operations: when the belt is indexed it moves the processes sample *away* from the tool, while at the same time transporting the yet-to-be-processed sample *to* the tool. In this manner the cycle time calculation only counts one indexing cycle, which leads to a reduced overall cycle than what was previously thought.

4.3.1 First Generation Nanomanufacturing Machine

Next, the support structure for the belt (material transport system) and the workpiece fixturing mechanism (material handling system) were designed. The material transport system was supported by rollers, and for this first-generation model the linear motor from the sketch-model was again utilized to drive the belt. This can be seen in Figure 1.3. The section-view seen here is a cut along the long-axis of the tube, in the direction of belt-motion. The first-generation nanomanufacturing machine can be seen in Figure 4.17, with key features labeled.

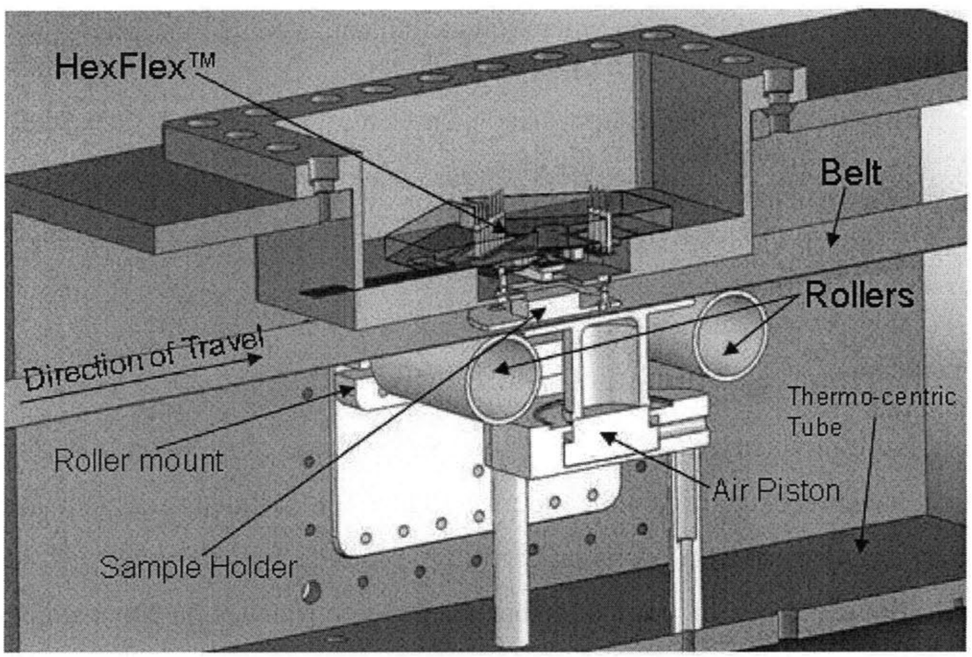

Figure 4.16: 3-D section-view model of the first generation nanomanufacturing machine with key features labeled.

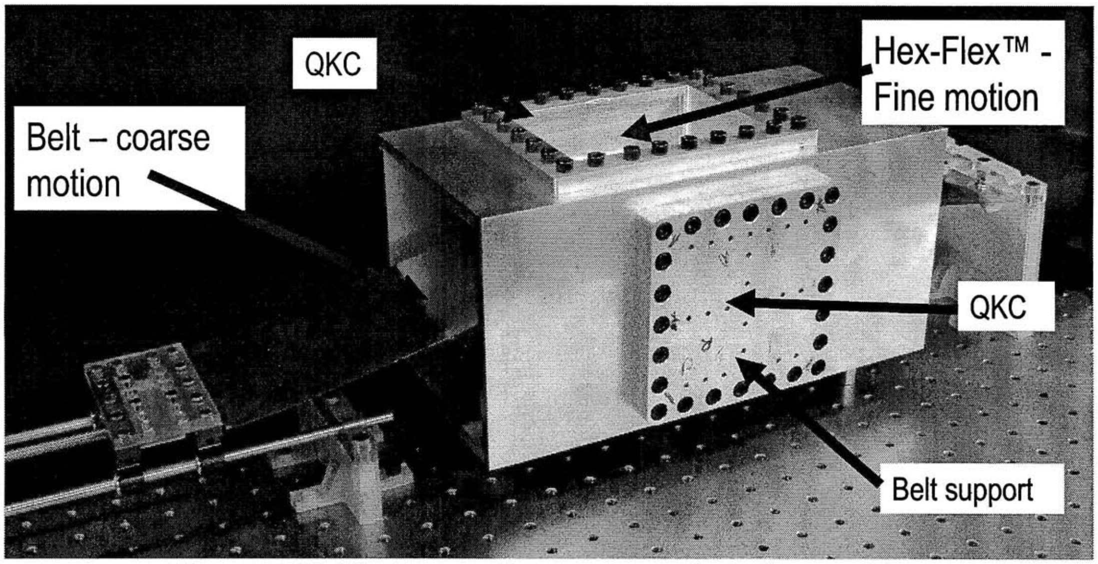

Figure 4.17: First-generation nanomanufacturing machine.

The ability of the first generation nanomanufacturing machine to meet the needs of the various types of nanomanufacturing processes was assessed by measuring the performance of the different kinematic couplings (both "quasi-" and "non-quasi-") in the material transport and material handling (fixturing) systems.

4.3.2 Performance of Flexure-Modified Kinematic Couplings

The flexure-modified kinematic coupling performance can be seen in Figure 4.18. The initial concept had a repeatability on the order of 20 nms [68], while this kinematic coupling has a repeatability of 300 nms. The air piston used to pre-load this coupling resulted in a relatively violent application of force; the pre-load happened almost instantaneously which could result in damage to the kinematic coupling's ball and groove surfaces.

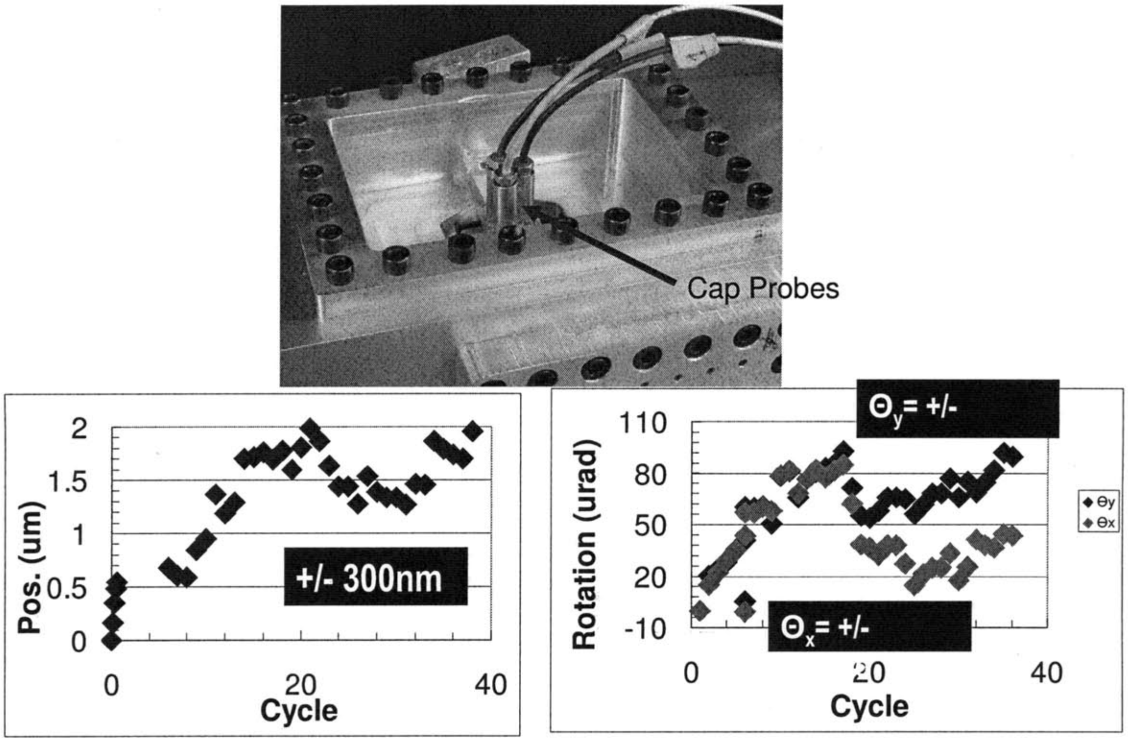

Figure 4.18: Sample-holder flexure-modified kinematic coupling performance.

While 300 nms is a respectable value for repeatability, there is error associated with friction between the sample and the belt, as well as the un-controlled manner in which pre-load force is applied. The first reaction to reducing the sample/belt stiction is to utilize a flexure, but the relatively high acceleration/deceleration induced by the operation of the belt drive would induce severe resonance and instability in a flexure-system with little damping. To address these needs, during a design review for the development of the second generation machine, it was suggested to integrate an air-bearing into the pre-load mechanism in order to eliminate the source of kinematic coupling error associated with the presence of friction between the belt and the sample holder (and thus eliminate the need for a flexure).

4.3.3 Performance of Quasi-Kinematic-Couplings

In the first generation nanomanufacturing machine, there were 3 quasi-kinematic coupling (QKC) interfaces manufactured: two large insert/material handling quasi-kinematic couplings and 1 hex-flex insert quasi-kinematic coupling. The hex-flex insert QKC performance can be assumed to be of the same order of magnitude as the material-handling insert QKCs.

Figure 4.19 shows a plot of module accuracy and repeatability; Figure 4.20 and Figure 4.21 show the accuracy and repeatability of the material handling inserts and the module mounting structure quasi-kinematic couplings.

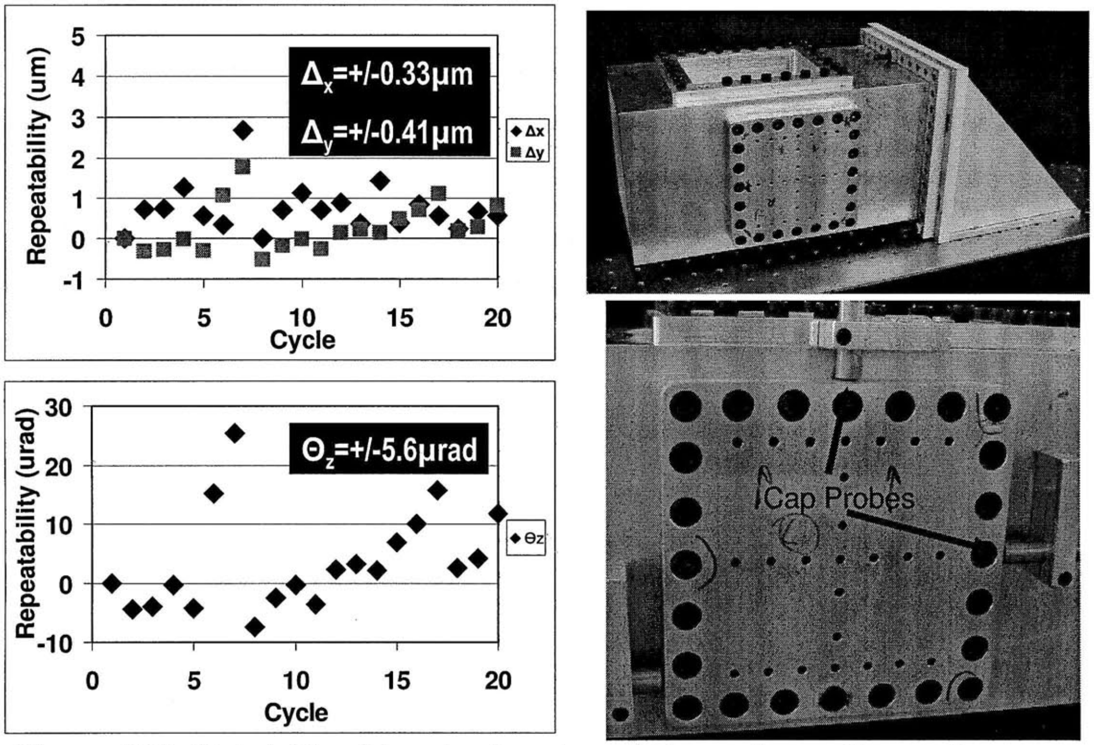

Figure 4.19: Material handling plug insert quasi-kinematic coupling performance.

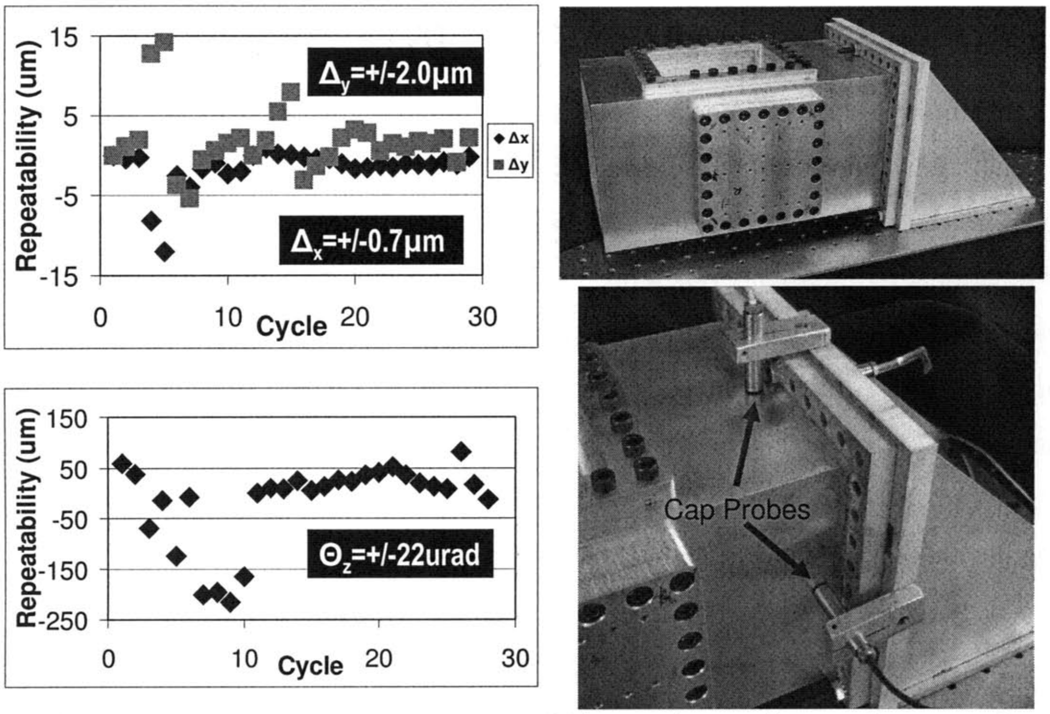

Figure 4.20: Module mounting structure quasi-kinematic coupling performance (part 1).

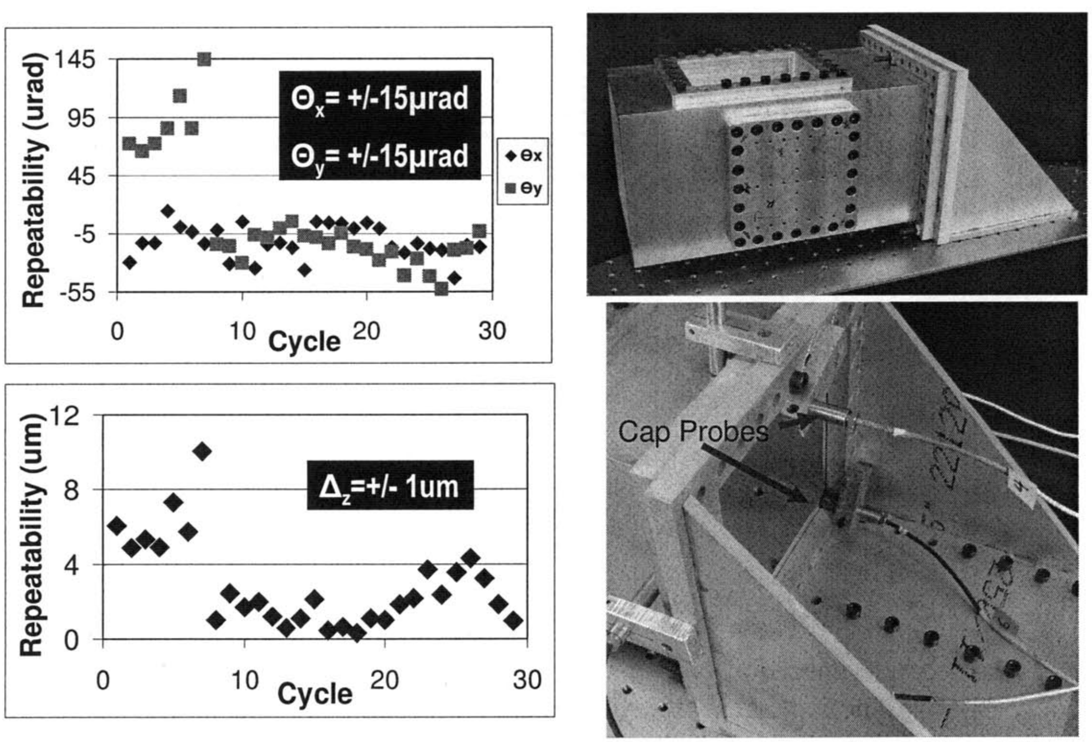

Figure 4.21: Module mounting structure quasi-kinematic coupling performance (part 2).

4.4 Second Generation Nanomanufacturing Machine

After multiple design reviews, solid-model iterations, and a lot of FRDPARRC-ing, the second generation nanomanufacturing machine was modeled, focusing on improvement to the first-generation material transport and material handling systems. This led to the additional of another functional requirement. When pre-loading kinematic couplings one significant source of error are frictional forces between the body of the coupling and the instrument used to apply the fixturing force; these forces can decrease the coupling's ability to seat properly and lead to decreased accuracy and precision. The solid model is shown in Figure 4.32, both as an isometric view (top), and a cut-away view (bottom) which shows the internal features of the machine, including the air bearing, belt-drive motor, and perforated belt.

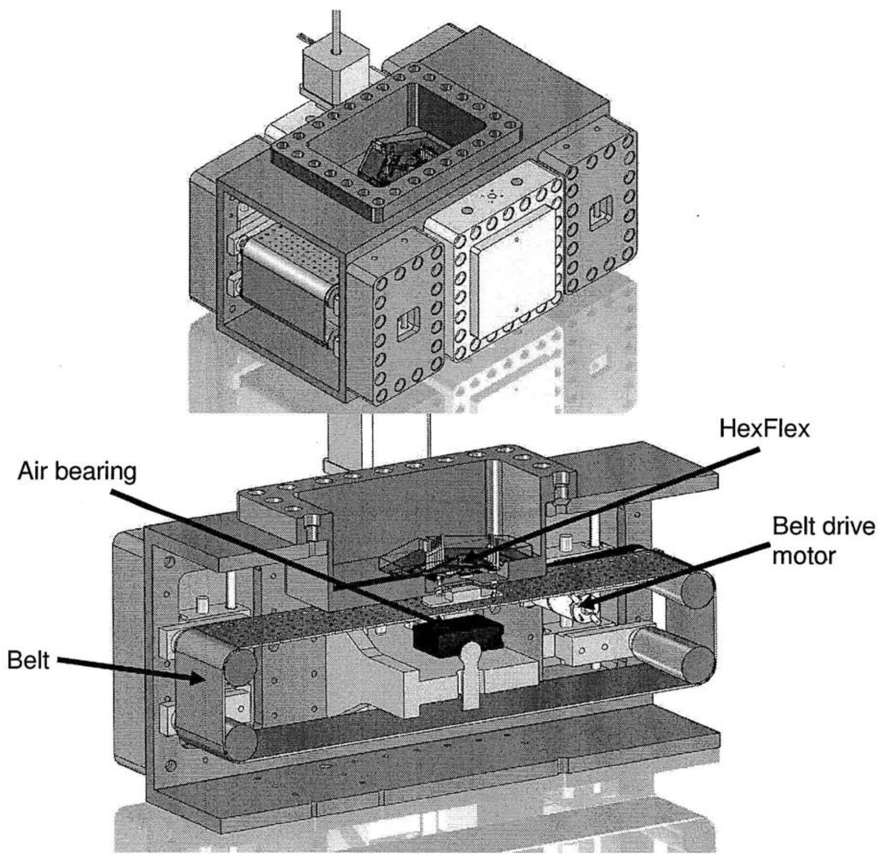

Figure 4.22: Second generation Nanomanufacturing Machine; isometric view (top) and cut-away view (bottom) show the general layout of the machine's components.

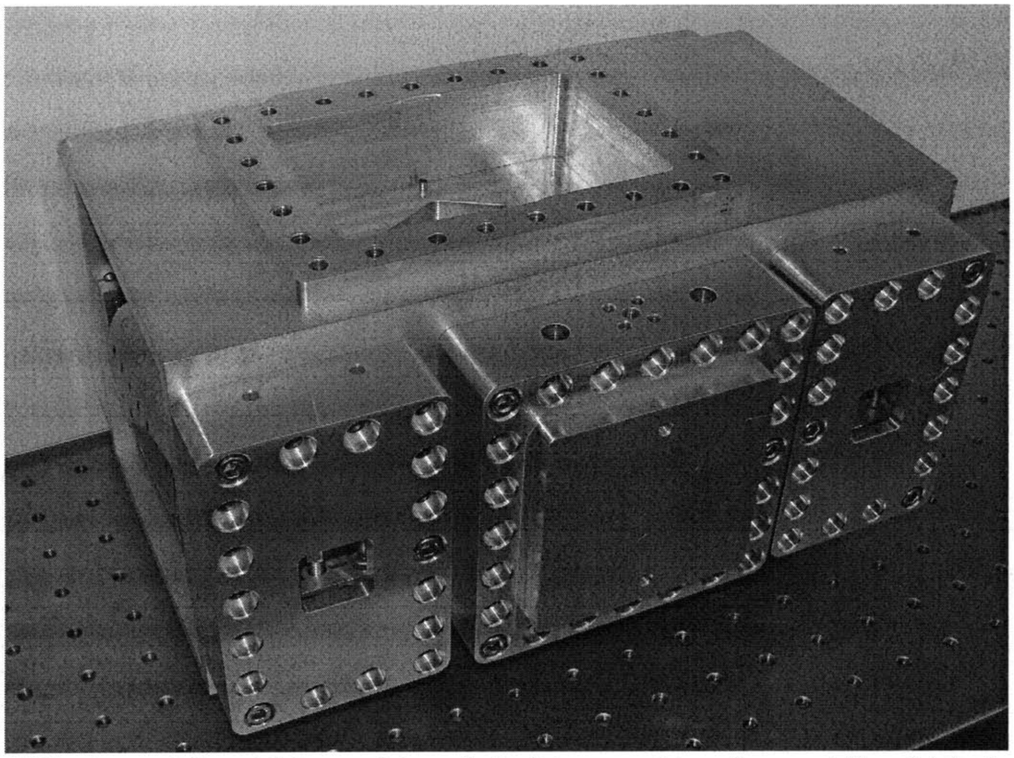

Figure 4.23: A modular, high-precision, belt-drive machine for enabling high-throughput nano-scale manufacturing.

In sections 4.4.1 through 4.4.3, the machine is described in detail and solid models are shown to highlight the components, coupled with pictures of the physical components to show how they are integrated into the machine.

4.4.1 Nano-positioning System

This nanomanufacturing machine utilizes a meso-scale, six-axis nano-positioner called a Hex-Flex, which was developed by Prof. Martin Culpepper in the Precision Compliant Systems lab at MIT. Table 4.3 is a recreation of Table 7.1: Case study nanopositioner requirements from a PhD thesis executed in the PCSL lab, that shows the desired and actual performance of a HexFlex^{TM} nanopositioner similar to that used in the nanomanufacturing machine [70]. This shows that the nanopositioner performance must be verified in achieving the desired z motion before being integrated into the machine, while this nanopositioner happened to not meet those requirements.

Table 4.3: HexFlex™ nanopositioner performance parameters.				
		Desired	Actual	
Range	x	± 10	± 18.2	μm
	y	± 10	± 15.7	μm
	z	± 30	± 2.6	μm
	θ_x	± 0.5	± 3.7	mrad
	θ_y	± 0.5	± 5.8	mrad
	θ_z	± 0.1	± 33.5	mrad
Resolution	x	15	22	nm
	y	15	37	nm
	z	10	3	nm
	θ_x	25	320	μrad
	θ_y	25	2	μrad
	θ_z	50	39	μrad
1st Mode		>50	~100	Hz
Cost (w/o DAQ)		<1000	~500	$ US

4.4.2 Material handling System

The material handling system consists of a single linear stage, driven by a linear motor, which provides accurate linear motion which is used to pre-load the sample against the sample kinematic coupling. The current design takes advantage of an already purchased, readily available linear motor (previously used in the sketch-model proof-of-concept system), sacrificing elegance for functionality and cost-effectiveness. Additionally, backlash in the linear motor is mitigated by the springs mounted on each of the shafts supporting the linear stage. Figure 4.24 shows a solid model of the material handling system.

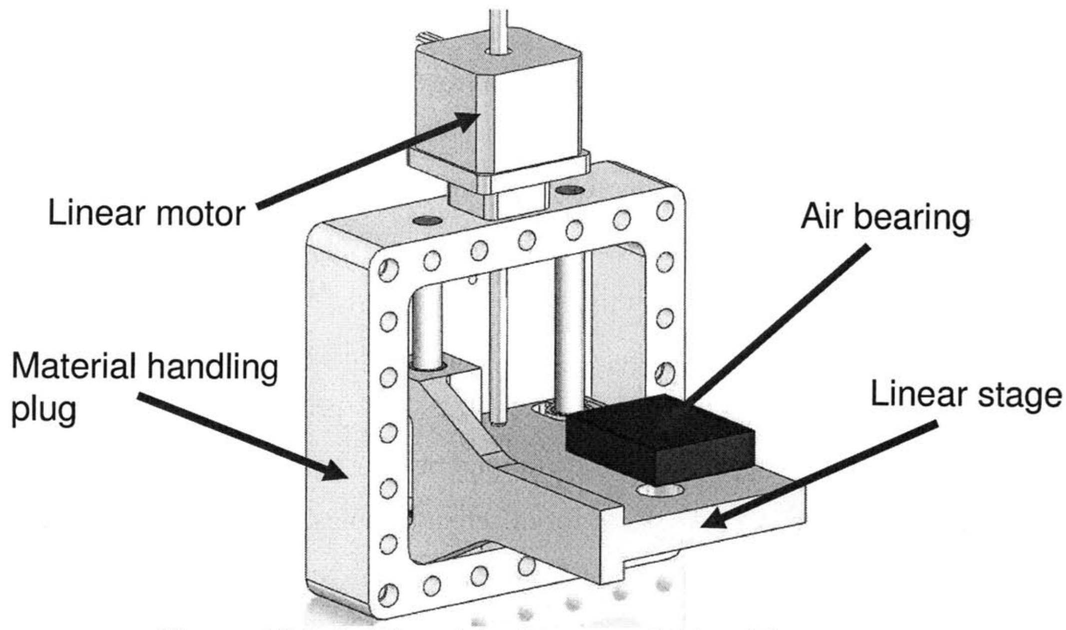

Figure 4.24: Solid model of the material-handling system.

The linear stage is a single block of 6061-T6 aluminum which will deflect about 80 microns given a 5 pound pre-load force. This deflection is on the order of 10% of the capture distance for the kinematic coupling. The free-body diagram used to represent this loading condition, along with the deflection calculations, are shown in Figure 4.26: Material-handling system installed in the nanomanufacturing machine..

Deflection Calculation			
Parameter	Value	Units	Symbol
Estimated Preload	5	lbs.	P
Moment arm	3.56	inches	m_a
AL young's modulus	1.00E+07	psi	E_al
Deflection	0.003	inches	
Deflection (mm)	0.084	mm	
	84	microns	
Moment of Inertia Calculation			
Parameter	Value	Units	Symbol
Width	1.75	inches	b
Height	0.25	inches	h
Moment of Inertia	0.0023	inches^4	I

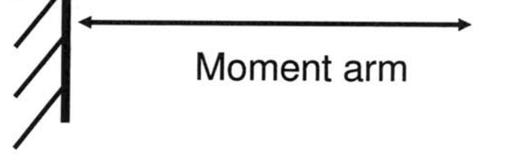

Figure 4.25: Material-handling system deflection calculations (left) and free-body diagram (right).

The air-bearing (purchased from New Way Air Bearings[5]), which was integrated into the system to eliminate sources error associated with applying pre-load forces to he workpiece, was selected based on the characteristic size of the typical working area currently used for fabricating nano-scale products. Existing DPN technology operates on an area that is one centimeter square, and the air bearing which is currently being utilized is 40x50 mm. The air bearing is larger because the one-centimeter square working area requires a supporting flange (to which the flexure-modified kinematic coupling components are mounted, as seen in Figure 4.27) that is on the order of four centimeters. (40mm).

However, the mounting hardware for the air bearing is standard so that different size bearings can easily be placed in the system for different samples. This is another example of the elegance of the modular design and being able to accomodate a wide range of nanomanufacturing processes, workpiece sizes, and process requirements. The material handling system, including the linear stage and air bearing, integrated into the nanomanufacturing machine is shown in Figure 4.26.

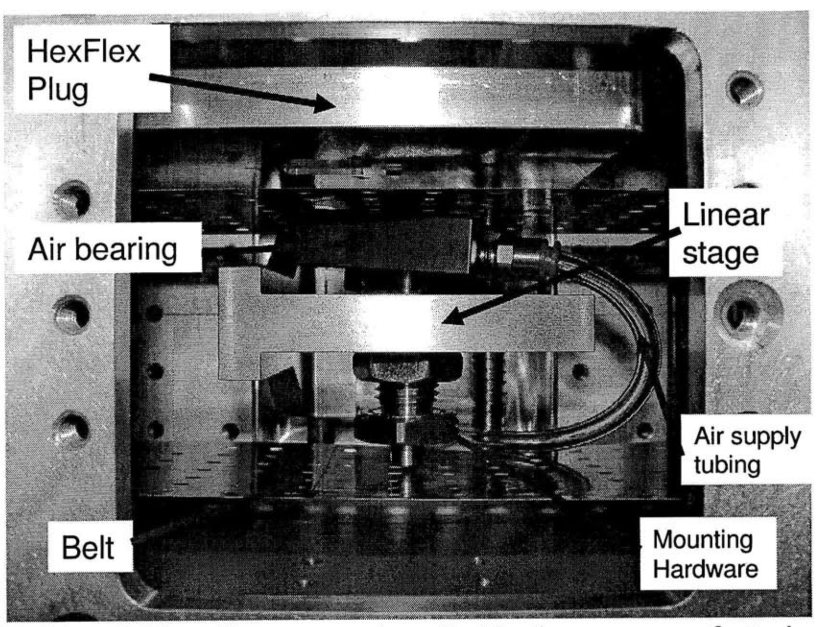

Figure 4.26: Material-handling system installed in the nanomanufacturing machine.

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[5] www.newwayairbearings.com

The material handling system, as stated before, is tasked with pre-loading the sample, or workpiece, relative to the tool. Figure 4.27 depicts an example of what a workpiece could look like; the raised platform in the middle offsets the surface towards the HexFlex, and also helps to mitigate abbe error by bringing the surface being worked on by the tool up to the plane of the fixture. The flexure-modified kinematic coupling components (the balls are mounted on the workpiece, and the grooves on the underside of the HexFlex plug) are clearly visible in the top figure. In the bottom figure, a down-tube view of the workpiece is shown, where it is clearly fixtured to the corresponding grooves in the underside of the HexFlex plug.

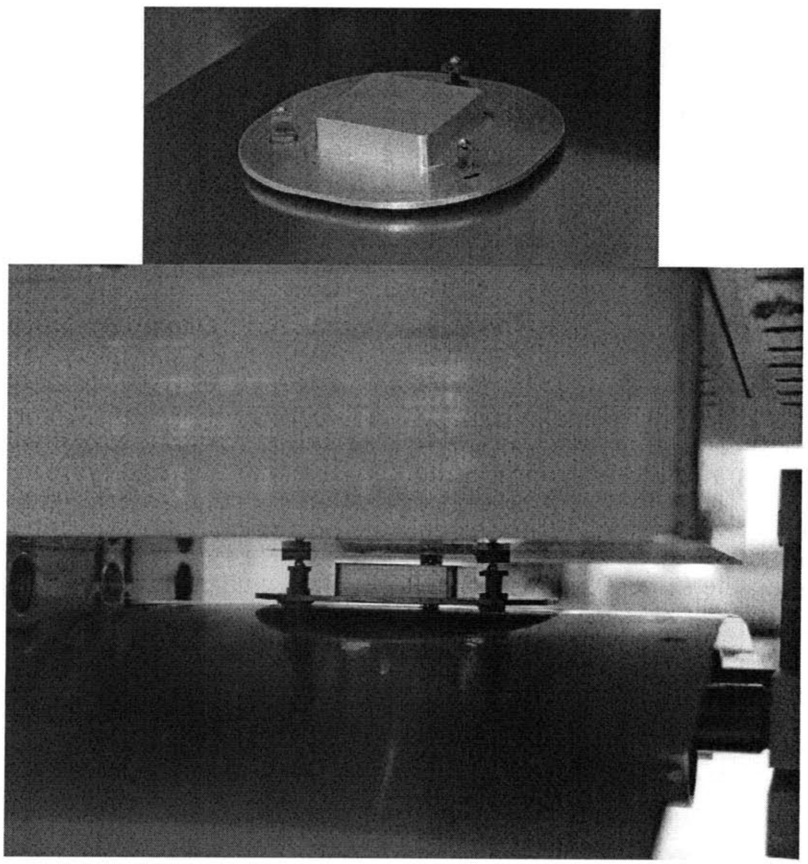

Figure 4.27: Example of a sample/workpiece, with flexure-modified kinematic couplings.

4.4.3 Material Transport System

The belt-drive system utilizes similar (but smaller) plugs to those used to fixture the material handling system to the superstructure of the nanomanufacturing machine A solid model of the material transport system can be seen in Figure 4.28. Key features are labeled, including the plugs used to support the belt tensioning and drive systems, as well as the belt shown supporting a sample workpiece in the figure. The access ports are used to adjust belt tension, as well as insert the mounting screws which affix a roller to the corresponding linear stage.

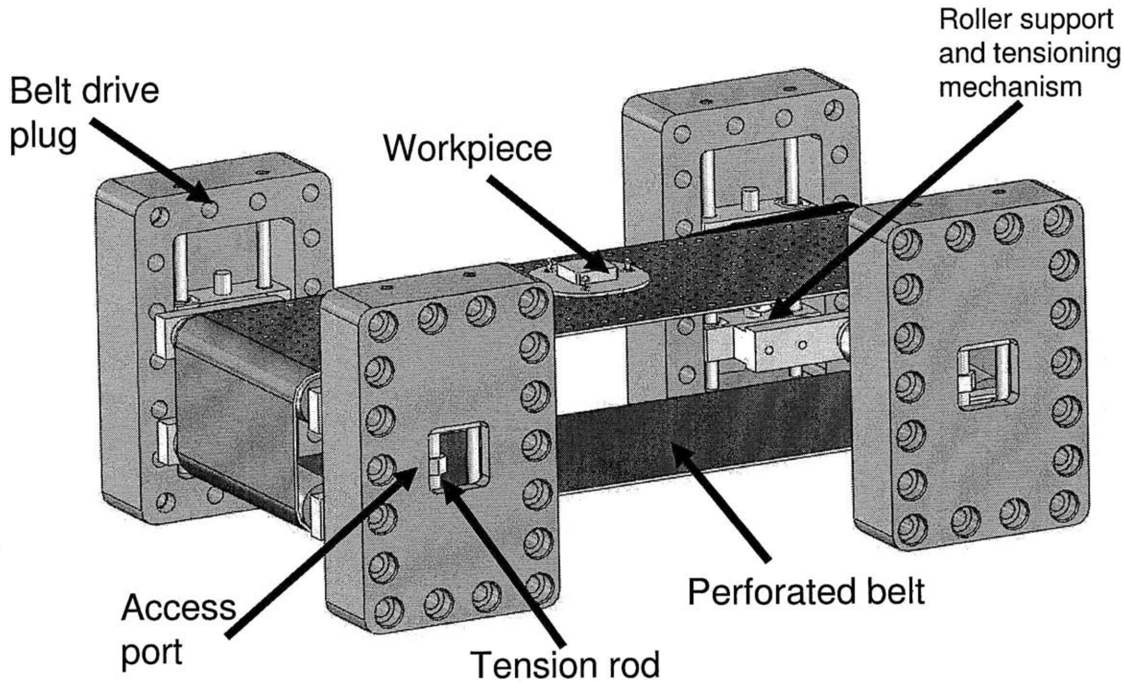

Figure 4.28: Solid model of the material transport system.

The motor used to drive the system was sourced from Maxon Motor USA[6]. The power budget used to determine the appropriate motor size is shown in Figure 4.29. The rotational inertia for the rollers was assumed to be equal for four times that of a single roller (as they are not all rotation about the same axis), while the torque to actuate the belt was assumed to be equal to the torque required to accelerate a point mass (equal to the mass of the belt) at a radius equal to that of the roller. The toothed belt used to transmit power from the motor to the belt drive driveshaft uses two pulleys of the same diameter.

[6] www.maxonmotorusa.com

Parameter	Value	Units	Symbol
Radius of roller	**0.375**	in	r_rol
Mass of belt	**1.43**	lbs	m_belt
Belt Intertia	0.20	lbs*in^2	b_I
Roller Inertia	**0.01**	lbs*in^2	r_I
Number of rollers	**4**	n/a	num_rol
Composite Inertia	0.24	lbs*in^2	comp_I
Composite Inertia (N*m^2)	7.06E-05	N*m^2	comp_I
Roller center distance	**11**	inches	rcd
convert to meters	0.28	meters	
Transfer time	**5**	seconds	t_t
Maximum acceleration	0.01	m/s^2	max_a
Angular acceleration	0.03	rad/s^2	ang_a
Required motor torque	0.007	Nm	
Req'd torque (mNm)	**7.14**	mNm	mot_torq
Req'd torque (oz-in)	1.01	oz-in	

Figure 4.29: Belt drive motor power budget.

Each plug contains a version of the assembly shown in Figure 4.30. One assembly has a modified component to which the belt drive motor is mounted. There are 8 total such mounts (2 for each roller), which are attached to a single linear stage; each roller is supported by 2 ball bearings. These linear stage pairs are connected by a counter-threaded rod (tension rod), the opposing left and right-handed threads utilized to move the stage pairs apart from each other (increase tension) and towards each other (decrease tension).

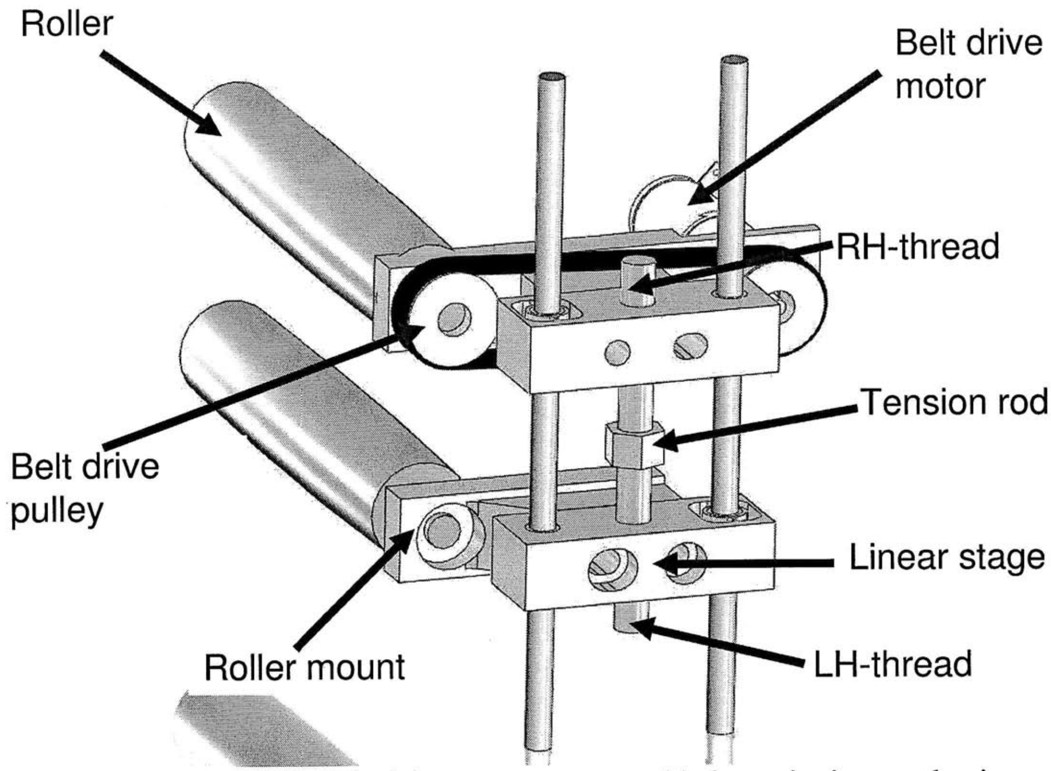

Figure 4.30: Solid model of the motor mount and belt tensioning mechanism.

Each linear stage pair is also constrained by springs above and below; the springs oppose each other and set a "dc height" for the belt. When the linear motor applies a pre-load force to the workpiece (sitting on the belt), the belt translates upwards to accommodate for this movement. The belt drive system can be seen integrated into the nanomanufacturing machine structure in Figure 4.31.

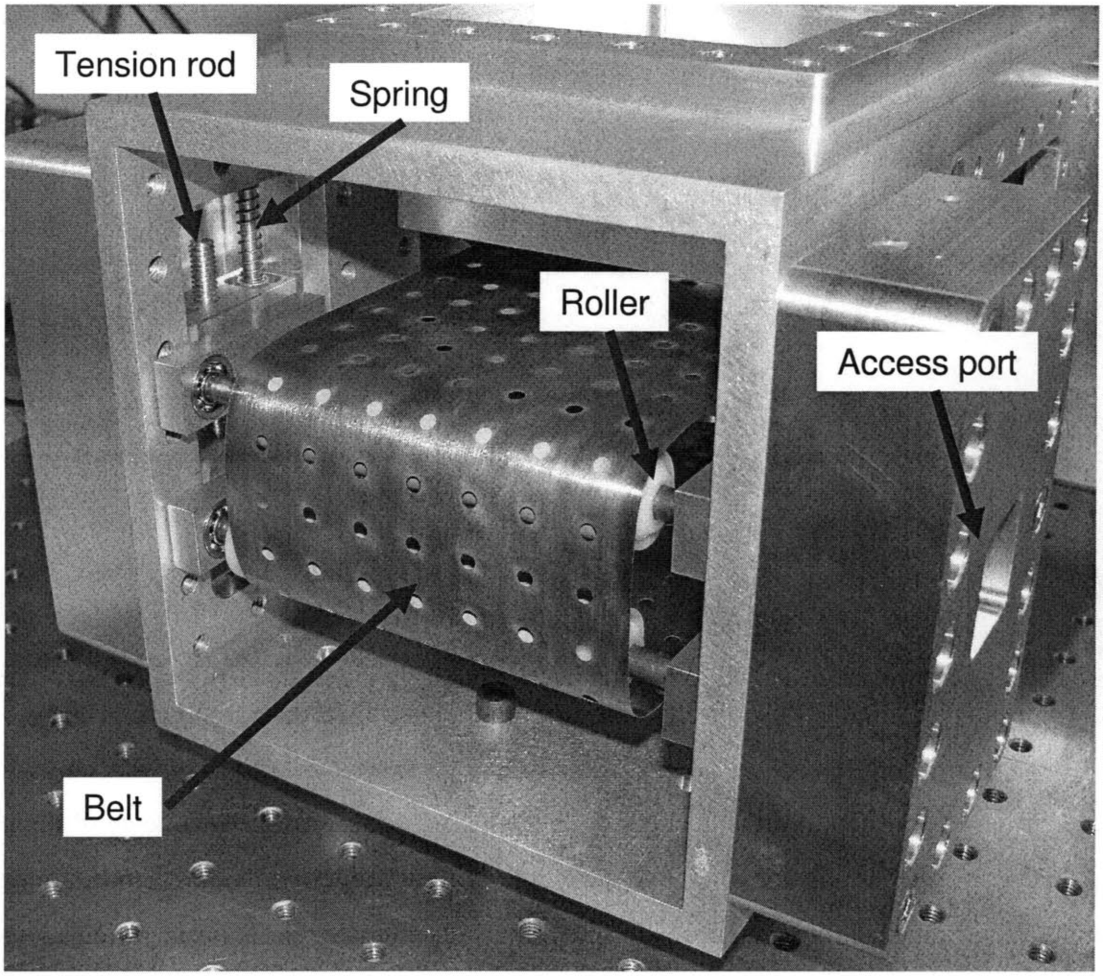

Figure 4.31: Belt-drive system integrated into the nanomanufacturing machine.

4.4.3.1 Perforated Indexing Belt

The perforated belt used in this machine was fabricated on an Omax Waterjet. Type 300 stainless steel shim-stock 100 microns thick was attached to a sheet of nylon with double-sided tape, then covered with duct tape. The pattern of the belt was cut out, with tabs on the ends left for post-processing. The belt was then laser-welded by Belt Technologies, Inc. [71]. There is no visible discontinuity at the weld line in the belt cross-section when bent, and the surface is very smooth. The belt in various stages of production, and the final product, can be seen in Figure 4.32.

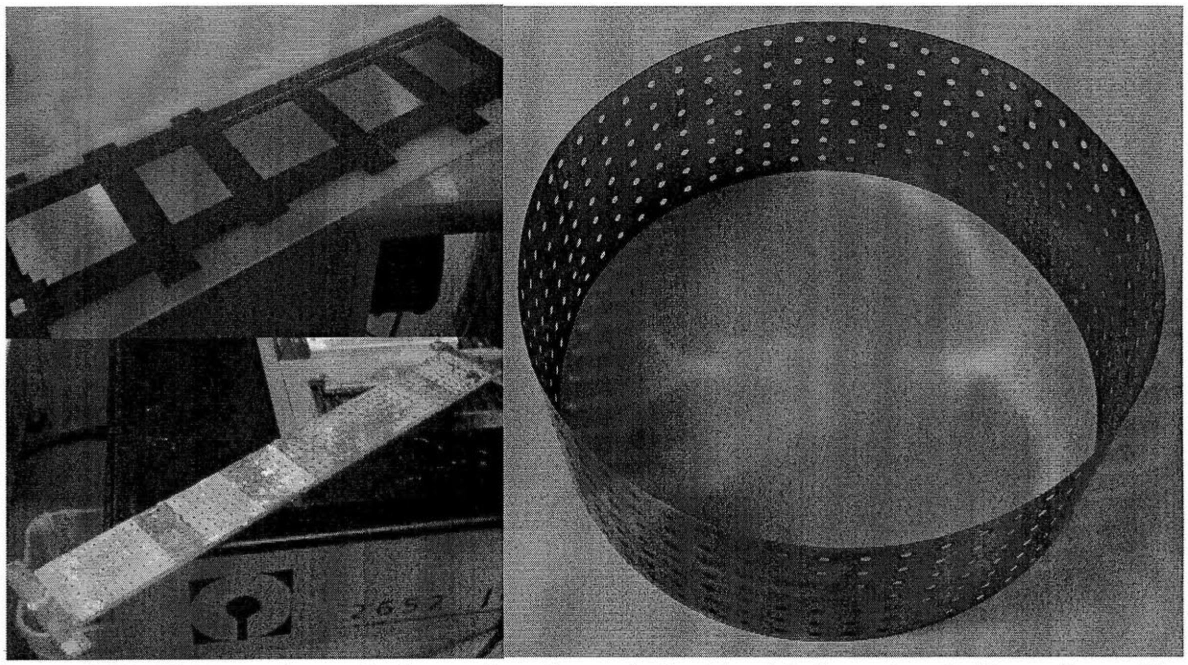

Figure 4.32: Shim stock attached to nylon sheet via double-sided tape(top left); perforated belt post-waterjet (bottom left); laser-welded perforated nanomanufacturing belt (right).

Further experimentation is needed to determine the long-term performance of the belt and weld; this would be applicable in the latter stages of the development of a production-ready nanomanufacturing machine based on the machine presented herein. The supplier advised that the standard welded belt they were capable of producing could achieve accuracies on the order of several microns, well within the kinematic coupling capture distance, and thus sufficient for this application.

Additionally, according to the manufacturer, the belt would be viable for on the order of a couple million revolutions. The current belt is 27 inches long; if one sample is processed for every three inches of belt, then one revolution will yield 9 samples. Thus a single belt could be used to process on the order of 27 million samples. For the DNA experiment detailed in Figure 4.2, which will utilize about three million samples, 9 of these experiments could be enabled using a single belt. However, this is assuming continuous movement of the belt. The stop/start nature of the machine operation needs to be analyzed and a model needs to be developed in order to determine the true belt cycle limit.

4.5 Machine Operation

During the course of this research, multiple non-scientific factors caused DPN to no longer be a viable processes. A switch to a template-based PDMS stamping operation was made, and is now currently being implemented using this machine. DPN is a scanning-probe based process, while PDMS stamping is a template-based process used to apply an ink to the surface of a silicon wafer. While a tip array used in DPN has cantilevered tool tips that mitigate the effects of small misalignment, PDMS stamping will require much tighter tolerances on tool/workpiece alignment to achieve acceptable process yield.

The small-scale devices used in micro-fluidic features that are stamped into the PDMS sample have feature sizes on the order of 10s-100s of microns, however in order for them to function well, the tolerance on these features is on the order of 10-100s of nanometers. This means the planarity requirement of 800μrad for DPN is now reduced to on the order of 5 - 10 μrad for accurate, high-yield PDMS stamping operations. This will be pushing the current limits of the flexure-modified kinematic coupling. Special care was taken to properly assemble the new flexure-modified kinematic couplings for the PDMS sample holder, as well as those which would support the HexFlex^{TM}, and all coupling surfaces were coated with high-performance white lithium grease prior to implementing the process.

Testing of the nanomanufacturing machine's ability to stamp small-scale features using a PDMS stamp is ongoing. In conclusions, a nanomanufacturing machine has been designed and built, and demonstrated to be able to meet the unique functional requirements of two nanomanufacturing processes. Future work will include activities such as enabling other nanomanufacturing processes, and building a nano-transfer manufacturing line using multiple modules; this is discuss further in Chapter 5.

CHAPTER

5

CONCLUSIONS: THE FUTURE OF NANOMANUFACTURING

5.1 Technology Development

This thesis seeks to educate the reader about the history of manufacturing, and how the evolution of machine tools for macro-scale manufacturing can be mapped to the design of new machine tools and new technology for nano-scale manufacturing. The Metric Mapping process is presented for a design engineer to use as a framework to aid in the creation of new technologies and machines for enabling the mass-manufacturing of nano-scale products and materials. The METMAP process was demonstrated as applied to the selection of candidate macro-scale manufacturing processes which were then utilized as stepping stones to developing a modular, flexible nanomanufacturing machine capable of enabling the low-cost high-rate production of nano-scale parts.

A design engineer reading this thesis will hopefully come away with new ideas for designing machine tools for enabling nanomanufacturing. However, this thesis is not the ultimate solution to the problem that is lack of adequate technology for nanomanufacturing; it will still take a few years of engineers and scientists reading, experimenting with, and further developing their own ideas as well as the ideas presented in this thesis for major improvements to the nanomanufacturing technology field to become apparent.

5.1.1 Improvements to the Current System

The current nanomanufacturing system has been demonstrated to be capable of meeting the accuracy and precision requirements associated with enabling nano-scale processes.

However, as with any machine that is actively undergoing development and testing, there are areas which could be improved. For this machine the design/performance of the following machine elements provide the largest opportunities for improvement:

1. Linear stage/air bearing actuator
2. Belt tensioning system
3. Belt drive motor analysis

The actuator for the air bearing stage should ideally be integrated into the internal structure of the material handling plug; it is currently placed above the entire structure because it was the simplest, easiest solution at the time. This was done due to both time limitations and funding restrictions, as well as the desire to minimize the complexity of the 2nd generation machine. Small, high-precision linear motors could easily be integrated into the superstructure of the inserts

5.1.2 Nanomanufacturing Process Development

The development of a new nanomanufacturing processes could happen at any time, not to say that it is a bad thing or that it is unexpected; on the contrary, the development of new nanomanufacturing processes only serves to increase the potential breadth of the impact that nanotechnology could have on society. One issue that was apparent at the beginning of this thesis project was the disconnect between the scientist developing the new process and the end-user. While it is good to maintain focus on the task at hand, this can sometimes result in an unexpected case of "end-of-the-line" syndrome[7].

An individual developing a new process reading this thesis will hopefully learn about some of the considerations which must be addressed while designing precision machine tools for nanomanufacturing. This could in turn lead to a different direction of experimentation regarding the process parameters, or even an improvement to the process based on machine tool performance capabilities of which the individual was previously unaware.

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[7] Commonly referenced by the old man who retires from a factory assembly line after 50 years and says, "I'm going to the end of the line to see what we make here".

5.1.3 The Modular Nanomanufacturing System

One of the benefits of a modular, highly flexible "base" system is that it promotes the modification of various components and the creation of new inserts/modules to work with the current system. An additional iteration of the current system, using 1 of the 2 large modules for material handling/working, and 4 small modules for material transport could be modified to create an additional material handling/workpiece module downstream of the first module that would perform a second manufacturing operation, a metrology step, or a process verification step (verifying that the previous step was successful and yielded usable product).

The modularity aspect also gives this nanomanufacturing system the capability to be used with multiple different nanomanufacturing processes. A single base unit can be assembled with sets of different inserts, each set dedicated/fabricated specifically to enable a different nano-scale manufacturing process. In this regard a laboratory has essentially unlimited freedom to design and develop new nano-scale processes: they have been provided already with a generic actuator, material transport/handling system, and a machine architecture. Minor adjustments and the addition of a few small components can mean the different between a machine for enabling nano-imprint lithography and one for driving an entirely new process.

Additionally, the current system is fully able to be scaled up (or down) depending on the application. The size of the square extrusion can be changed to increase the cross-section, making the machine capable of processing/producing a large amount of nano-scale products. Furthermore, the cross-section can also be changed entirely; what if a specific process required a rectangular cross-section (lower aspect ratio of length to width, the current aspect ratio is 2)? The solution might be as simple as obtaining and belt and rollers which were wide enough to accommodate the now rectangular cross-section. Very little significant re-design of the machine structure/function could be required to enable a significant change in the function of the machine.

The processing of webs and/or long strips of material (i.e. coating with nano-products or devices) can also be achieved using this system. The METMAP process can be used to identify the best macro-scale technology for handling webs/material strips. An example of such macro-scale machines are those used in the newspaper industry to process the hundreds of thousands of newspapers published in the US every day. Some of these relatively simple technologies could be integrated with this modular design, giving nanomanufacturing engineers access to a testing platform for processing of webs and belts coated with nano-scale features.

5.1.4 Scaling Laws

In addition to modularity and flexibility, the design of a nanomanufacturing machine presented in Chapter 4 can very easily be scaled to meet different sized arrays. The development of scaling laws for this machine would most likely focus on further mitigation of thermal effects as the overall design increased in size, as well as issues of stability in the overall structure: a relationship between tube width/height and wall thickness would be an example of a scaling law that would create a "best practice" for the creation of larger nanomanufacturing machines. Some other scaling laws would address the physical behavior and performance of some of the following machine systems:

1. Increasing the belt-drive length and width
2. Pre-load mechanism deflection
3. Air-bearing performance
4. Contamination control (with a focus on seal design).

The belt-drive length and width would need to be increase to handle larger sample sizes, as would the calculation of pre-load mechanism deflection.

The air-bearing is cantilevered from one side of the tube, and thus deflection of the linear stage due to pre-loading forces increases by the cube of half the tube width. Increasing the size of the thermocentric tube from the current dimension of 150 mm to 200 mm (6" to 8") will increase the deflection at the air-bearing by a factor of about 2.25, from just over 80 microns, depicted in Figure 4.25, to almost 200 microns. This increase can be countered by increasing the size of the balls and grooves used in the kinematic coupling, thus increasing the KCs capture distance.

Scaling laws and design guidelines for machine elements such as the Quasi-Kinematic and Kinematic Couplings exist and can be referenced from the literature [72, 73]. Additionally, the design of a seal for this machine needs to be executed and implemented, then tested to further verify the performance of the air-bearing and it's use in creating a positive-pressure environment within the tube to further mitigate contamination.

5.2 Improvements to the Current Design

5.2.1 Belt Tensioning Mechanism

The belt tension mechanism can be improved, as seen in Figure 5.1, by adding an access port to the top of the belt-drive plug with which a modified tension rod can be access with a screwdriver or socket wrench. This will increase the amount of tension that can be applied to the belt, decrease the time it takes to change the amount of tension, and increase the ease with which tension can be adjusted. The current belt-drive plug side ports limit both the range of motion of a tool used to increase or decrease tension, which in turns causes changes in tension to take several minutes; this can very easily be reduced to several seconds using the simple modifications depicted in Figure 5.1.

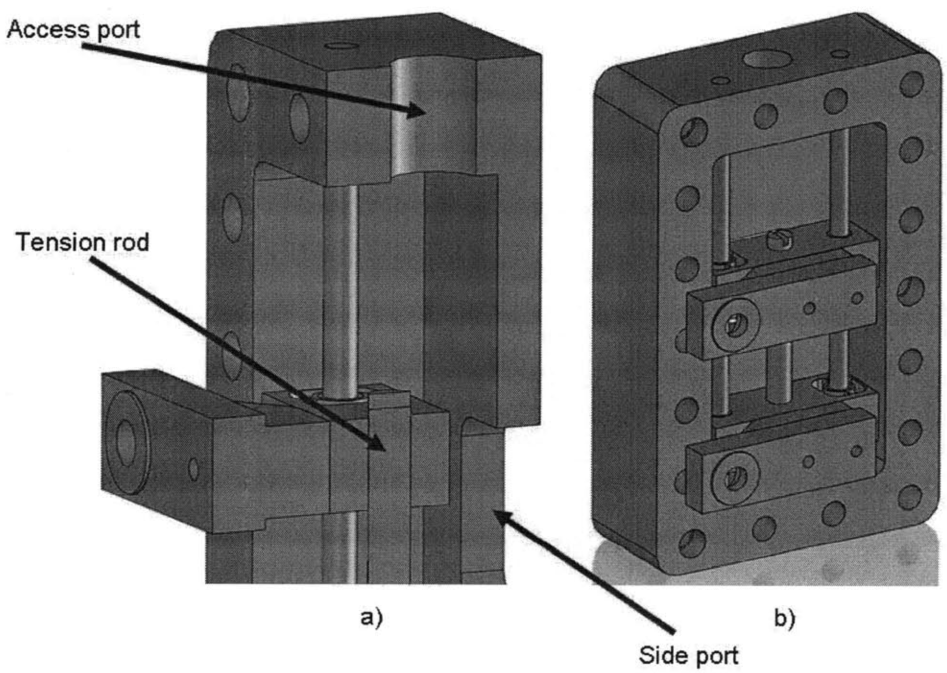

Figure 5.1: a) Cut-away view of the modified tension mechanism; b) isometric view of the modified belt-drive plug.

5.2.2 Pre-load Mechanism

The pre-load mechanism is currently driven by a linear motor that was the most cost-efficient and simplest way to achieve linear motor available at that point in the project.

Improvements to this design could involve the generation of more space, between the linear stage and the material handling plug, and placement of a small linear actuator attached directly to the stage, or rotary actuator which drives a screw that would move the stage. At first glance it would seem that the rotary actuator would be able to achieve a larger range of motion (ROM), as can be seen in Figure 4.32. Further deterministic evaluation of the

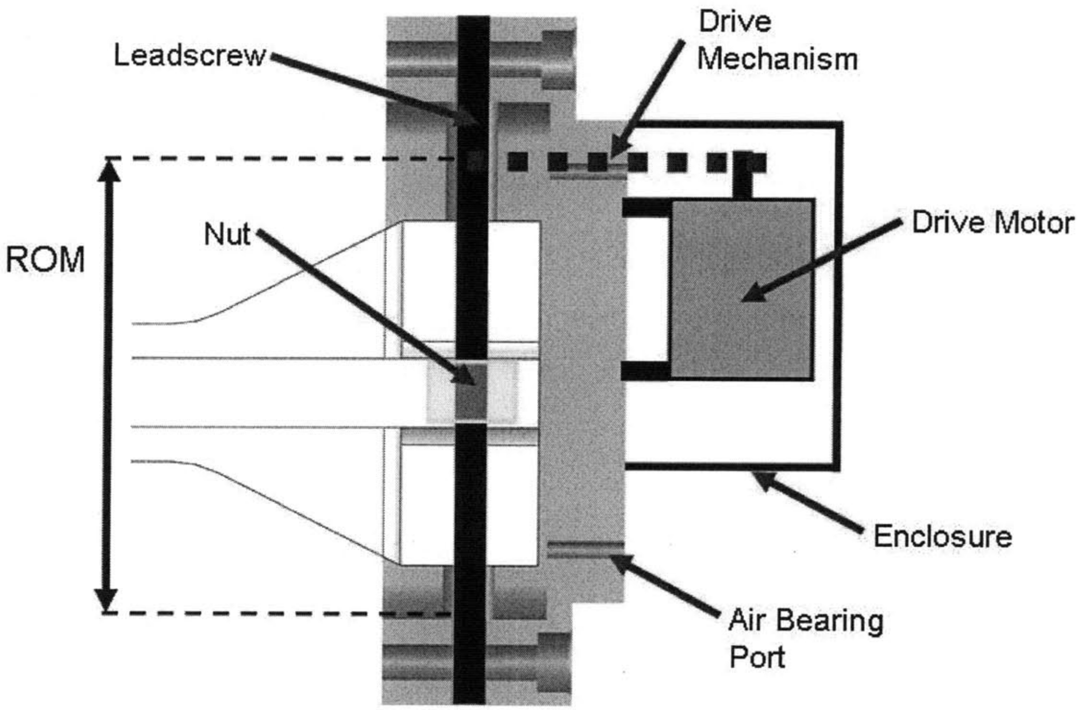

Figure 5.2: Schematic of a rotary-actuator-driven screw-type mechanism driving the linear stage. The range-of-motion is nearly the full height of the material handling plug.

5.2.3 Design for Continuous Processing

A design for continuous processing would require major modifications to the belt drive plugs, as well as possible elimination of the material handling mechanism. The material handling plugs could be modified to support rollers that would position the web or continuous material relative to the tool, which would again be mounted on the HexFlex™. In this embodiment of the machine, however, multiple hex-flexes would need to be used in a staggered formation so as to allow for total coverage of the area of the continuous material.

5.2.4 Nanomanufacturing Line

Implementation of a nanomanufacturing line, a schematic diagram of an example of such an assembly being depicted in Figure 5.3, would involve assembly of multiple nanomanufacturing machine modules. Buffers for each machine are not shown in this figure, but would need to be designed and implemented for accurate depiction of the behavior of the manufacturing line. Furthermore, the buffer design presents an additional opportunity for further technology development in the form of an autonomous buffer for receiving and delivering sample holders from and to the nanomanufacturing machine modules surrounding it. The optimal buffer design will most likely utilize are bearing technology so that samples are easily and simply transported from one module to another.

Step 1 in Figure 5.3 shows the assembly of coating, writing, and cleaning modules, with a metrology module added on to the end of the line for process verification. If, however, during testing of the nanomanufacturing line it is determined that the metrology module needs to be placed directly after the coating module , modularity of the nanomanufacturing machine is illustrated. It is a simple procedure to de-couple the coating and writing modules, and insert the metrology module in between them. This process would be facilitated in maintaining the overall precision of the nanomanufacturing line through the use of quasi-kinematic couplings (the location of such an interface is shown by the blue dashed line). Furthermore, a single belt is used in the figure for simplicity to represent the continuous flow of material through the system, whereas each individual module utilizes it's own belt for material transport.

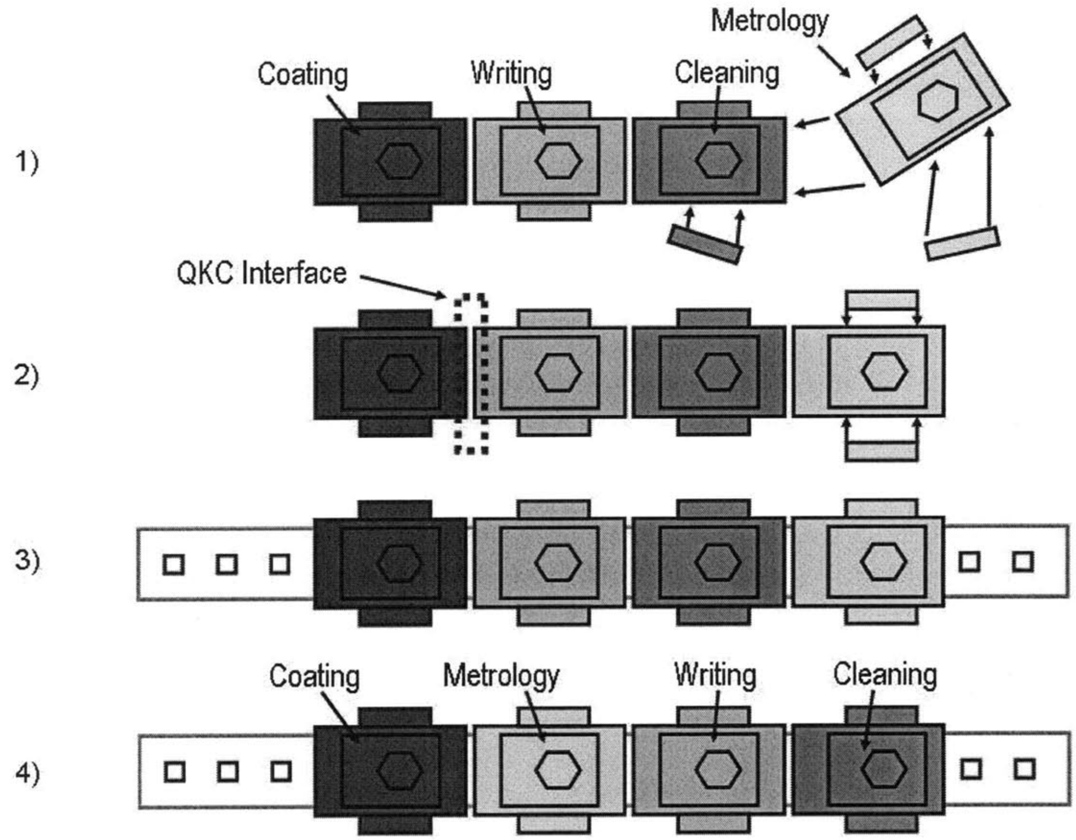

Figure 5.3: Schematic of a nano-transfer line being constructed. 1) The metrology module is being added to the end of the line, consisting of modules for coating, writing, and cleaning. 2) The location of a quasi-kinematic interface/flange is shown by the dashed line. 3) A "belt" is added to the nano-transfer line; this represents the individual belts located internal to each module. 4) The modularity of the transfer line is demonstrated when the metrology module is easily moved up the line to before the writing module.

These are the areas of the current machine which demonstrate opportunities for improvement with a high cost-benefit ratio, or large improvement for low cost/effort. Unfortunately, both time and funding constraints have placed a limitation on the depth and breadth with which additional future work can be discussed in detail. Another experiment that could be performed, in addition to the nanomanufacturing line, would be the implementation of a wide range of nanomanufacturing processes using the nanomanufacturing machine presented in this thesis and then performing a comparison of the products produced with this machine, with the original instrument used to implement the process, thus further verifying the ability of this modular, flexible, precision machine to efficiently and cost-effectively enable high-throughput nanomanufacturing.

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